Installation Restoration General Environmental Technology Development

REPORT NO. AMXTH-TE-CR-86074

Task 11.
Pilot Investigation of Low Temperature Thermal Stripping of Volatile Organic Compounds (VOC's) From Soil

Volume 1 - Technical Report

June 1986

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Prepared for:
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
Aberdeen Proving Ground (Edgewood Area), Maryland 21010

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. ADA 164439	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Installation Restoration General Environmental Technology Development. Task 11. Pilot-Scale Investigation of Low Temperature Thermal Stripping of Volatile Organic Compounds (VOC's) from Soil		5. TYPE OF REPORT & PERIOD COVERED Draft Final Report- May 1985 – February 1986
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Nancy P. McDevitt Peter J. Marks John W. Noland, P.E.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Roy F. Weston, Inc. Weston Way West Chester, PA 19380		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Toxic & Hazardous Materials Agency Aberdeen Proving Ground Edgewood Area, MD 21010		12. REPORT DATE February 1986
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution unlimited; approved for public release.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Contract Project Officer - Ms. Donna L. Koltuniak
(AMXTH-TE-D)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Volatile Organic Compounds (VOC's)	Afterburner
Low Temperature Thermal Stripping	Thermal Processor
Operating Temperature	Hazardous Substance List (HSL)
Residence Time	Volatization
Air Inlet Temperature	Soil Discharge Temperature

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a pilot investigation which successfully demonstrated the effectiveness of Low Temperature Thermal Stripping as a decontamination method for soils contaminated with volatile organic compounds (VOC's). The project included: process equipment and test site selection, waste characterization, development of a detailed test plan and safety plan, pilot investigation and evaluation of results.

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1. EXECUTIVE SUMMARY

Soils at several U. S. Army Material Command (AMC) installations have been contaminated with a variety of organic compounds as a result of past solvent handling practices. In many cases the contaminated soil has resulted in the degradation of underlying groundwater supplies.

In order to limit further contaminant migration, the U. S. Army Toxic and Hazardous Materials Agency (USATHAMA) is investigating technologies to effectively treat the contaminated soil. One treatment alternative is low temperature thermal stripping of volatile organic compounds (VOC's) from soil. A pilot study was conducted at Letterkenny Army Depot (LEAD) near Chambersburg, Pennsylvania from 5 August 1985 to 16 September 1985 to determine the feasibility of this technology for future remedial action projects at Department of Defense (DOD) installations.

Soils from the site of two lagoons that were apparently used for the disposal of organic liquids were chosen for treatment. This selection was based on the type, variety, concentration, and volatile nature of the compounds found in this area. Two types of soil existed at this site: fill soil and native soil. A grain size analysis indicated that the fill material consisted of gravelly sands, and the native soil consisted of sandy clay/sandy silt.

Soils were treated in a thermal processor, an indirect heat exchanger which was used to heat and consequently dry the contaminated soil. The net effect of heating the soil was to evaporate volatile contaminants in the soil. A carrier gas (i.e., air) was introduced to the unit to enhance contaminant removal. Contaminants in the off-gases were thermally destroyed in an afterburner.

The pilot investigation was completed in two phases. Phase I consisted of 18 test runs completed to evaluate the effect on VOC removal efficiency of varying operating conditions, i.e., soil discharge temperature, soil residence time, and air inlet temperature. The 18 test runs were designed in a matrix format to investigate three levels of soil discharge temperature: 50°C, 100°C, and 150°C; three levels of soil residence time: 30 minutes, 45 minutes, and 60 minutes; and two levels of air inlet temperature: ambient and 90°C. Phase I test runs were conducted from 5 August 1985 through 26 August 1985.

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Phase II of the Pilot study consisted of 10 "optimization" test runs. The purpose of the optimization runs was fourfold: 1) to evaluate the effect on VOC removal efficiency of varying operating conditions beyond the limits set for Phase I of the investigation (i.e., maximum soil discharge temperature and maximum soil residence time); 2) to evaluate the VOC removal rate along the length of the unit; 3) to evaluate the VOC removal efficiency associated with three "duplicate" test runs to determine if the treatment was consistent and comparable; and 4) to evaluate the VOC removal efficiency associated with reprocessing treated soils that still contained a VOC residual. Phase II test runs were conducted from 27 August 1985 through 16 September 1985.

The data from the pilot investigation was statistically analyzed using multiple linear regression techniques. The objective of the analytical approach was to develop simple linear equations that would identify those input or controlled variables that had a greater significant impact on the response variable of concern; in this case, the concentration of total VOC's in the processed soils. The statistical analysis techniques were successful. Simple linear equations which were statistically significant were developed for design of a full-scale system operating at low, medium, or high soil discharge temperature.

Based on review of the data associated with all test runs, the following conclusions are presented:

1. The low temperature thermal shipping technology is an effective means of removing VOC's from soil.
2. VOC removal efficiencies associated with an elevated air inlet temperature are generally lower than those associated with an ambient air inlet temperature.
3. An exponential relationship exists between VOC concentrations in the processed soil and those input and control variables determined to have a significant contribution in the statistical analysis.
4. Correlations developed to predict the VOC concentrations in the processed soil and soil discharge temperature are site-specific and applicable to three distinct soil discharge temperature ranges. The validity of the correlations for different soil and contaminant types is questionable.
5. Moisture in the feed soil and residence time are statistically significant variables in all correlations (i.e., low, medium, and high soil discharge temperatures).

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6. An organic vapor analyzer (OVA) can be utilized to estimate the VOC concentrations in the discharge air stream; however, the instrument manufacturer should be consulted to determine if the pump suction pressure is appropriate for the specific application.

7. A mobile mass spectrometer can be utilized to generate reliable qualitative information concerning VOC's in the discharge air stream. However, considerable attention needs to be given to sampling methods and quantitative instrument calibration.

8. Fugitive emissions of VOC's occurred from the time of excavation of soils to the time soils were fed to the thermal processor (estimated total VOC's fugitive emissions was 9.02 percent).

9. The low temperature thermal processor can be designed to achieve specific VOC clean-up objectives. The level of residual VOC's in the processed soil is a direct and predictable function of:

    (a) VOC concentration in the feed soil,
    (b) Processed soil temperature,
    (c) Soil residence time within the thermal processor,
    (d) Heat input rate to the thermal processor, and
    (e) Moisture content of the feed soil and processed soil.

    Depending on the VOC type and range of concentrations in the feed soil for a specific site, the other variables (i.e., processed soil temperature, residence time, heat input and moisture content) can be incorporated within the overall system design to achieve a wide range of target clean-up levels (i.e., 100 ppm, 10 ppm, 1 ppm, etc.). However, if the clean-up objective is "no detectable VOC's in the processed soils," then, based on this field demonstration program, a processed soil temperature of higher than 233°C and a residence time of over 90 minutes would be required.

10. Treatment is reproducible and comparable if feed soil composition/conditions are similar (i.e., moisture, VOC concentration).

11. Reprocessing of treated soils that still contained a contaminant residue reduced the VOC concentration significantly; however, a residual still existed.

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12. Stack tests conducted during Test Runs 8, 9, and 10 indicated that no detectable levels of the principal organic hazardous constituents (POHC's) were present in the exhaust emissions (i.e., 100 percent destruction removal efficiency (DRE)).

13. Stack tests conducted during Test Runs 8, 9, and 10 demonstrated that particulate and hydrogen chloride emissions did not exceed regulatory limits during these test runs. (No comment can be made regarding other test runs as no stack testing was completed.)

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2. INTRODUCTION

2.1 <u>Background</u>. Soils at several U.S. Army Material Command (AMC) installations have been contaminated with a variety of organic compounds as a result of past solvent handling practices. In many cases the contaminated soil has resulted in the degradation of underlying groundwater supplies.

In order to limit further contaminant migration, the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) is investigating technologies to effectively treat the contaminated soil. One treatment alternative is low temperature thermal stripping of volatile organic compounds (VOC's) from soil. A pilot study was conducted at the Letterkenny Army Depot (LEAD) near Chambersburg, Pennsylvania from 5 August 1985 to 16 September 1985 to determine the feasibility of this technology for future remedial action projects at Department of Defense (DOD) installations.

2.2 <u>Purpose</u>. The purpose of this report is to present the results and conclusions of a pilot investigation that evaluated the concept of low temperature thermal stripping of VOC's from soil. A description of test conditions and process equipment is contained herein.

2.3 <u>Objectives of the pilot study</u>. The primary objective of the pilot investigation was to determine the feasibility of the low temperature thermal stripping technology for future remedial action projects at DOD installations. Secondary objectives included:

(a) Determination of the impact of varying design parameters on system performance (e.g., operating temperature, residence time, air temperature, etc.).

(b) Determination of the optimum range of operational parameters for the pilot system.

(c) Identification of full-scale design criteria.

(d) Evaluation of the off-gas pollutant levels to determine if air pollution control devices are required for full-scale implementation of the process.

(e) Preparation of engineering cost estimates for application of this technology.

(f) Identification of any future research needs for system optimization.

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2.4 _Report organization_. The information contained in this report has been organized into 13 sections:

Section	Title
1	Executive Summary
2	Introduction
3	Test Site
4	Description of the Process Equipment
5	Pilot Study Framework
6	Typical On-Site Activities
7	Experimental Variables
8	Sampling Techniques and Analytical Methods
9	Presentation of Data
10	Analysis of Results
11	Comparison of Test Results to Regulatory Criteria
12	Full-Scale Design Considerations
13	Conclusions and Recommendations

References cited throughout the report are provided in a separate listing at the end of the report.

The Appendices (Volume 2) provide additional data and analyses:

Appendix	Title
A	Organic Waste Characteristics of Site Soils at LEAD (determined during preliminary investigations)
B	Grain Size Gradation Curves Corresponding to Fill Soil and Native Soil
C	Air Sampling Techniques
D	Federal Regulations
E	Analytical Methods
F	Field/Analytical Data
G	Mass/Energy Balances
H	Supplemental Data
I	Statistical Analytical Approach

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3. TEST SITE

3.1 <u>Test site location and description</u>. The pilot study was conducted at the Letterkenny Army Depot (LEAD). LEAD, formerly known as Letterkenny Ordnance Depot, consists of 7,899 hectares (nearly 20,000 acres) of land situated in the south-central section of Pennsylvania in Franklin County, near the city of Chambersburg. A site location map for the installation is presented in Figure 3-1.

LEAD was established on 7 January 1942 with the mission of ammunition storage. The present expanded mission of LEAD includes the receipt, storage, inventory, maintenance, and demilitarization of ammunition; the overhaul, rebuilding, and testing of wheeled and tracked vehicles; and the issue and shipment of Class III chemicals and petroleum.[1] Some facility operations have included cleaning and stripping, plating, lubrication, demolition, chemical and petroleum transfer and storage, and washout/deactivation of ammunition.[2]

The pilot study was conducted in the East Patrol Road Disposal Area (EPRDA). EPRDA is located east of California Avenue, south and west of East Patrol Road, and north of Building 370. Approximate locations of the excavation and processing areas are shown in Figure 3-2. The processing area was located approximately 300 feet north and 260 feet west of the excavation area. For illustration, an aerial photograph of the excavation and processing areas is shown in Figure 3-3.

3.2 <u>Waste characteristics</u>. Previous efforts have identified and quantified the contaminants present in the site soils at LEAD. Brief descriptions of past investigations are included in the following subsections.

3.2.1 LEAD remedial investigation and feasibility study (RI/FS). A field sampling and analytical program was completed by WESTON in early June 1983.[1] The purpose of the program was to define and quantify the levels of contamination which existed at seven potential hazardous waste disposal sites located in the EPRDA. The locations of the disposal sites are shown in Figure 3-4.

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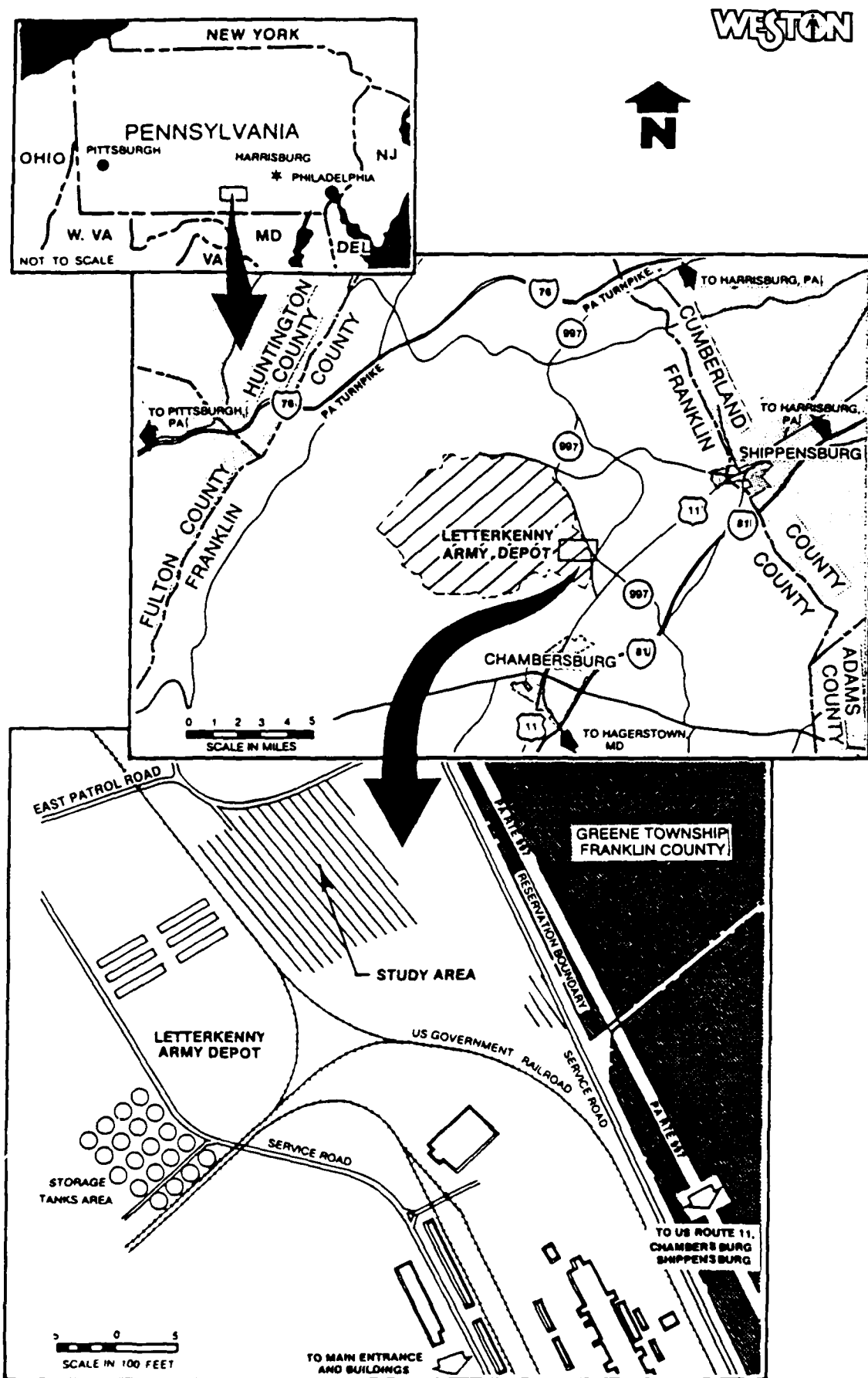
FIGURE 3-1   GENERAL LOCATION MAP OF THE STUDY AREA ON THE LETTERKENNY ARMY DEPOT, FRANKLIN COUNTY, PENNSYLVANIA

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Well E-1

Well E-3

Rail Road Tracks

Processing Area
40' x 40' Concrete Pad

Existing Dike

Existing Tankers

Existing Dike

Well E-5

Well E-8

Excavation Area

Well E-7

East Patrol Road

Electric Panel and
Gas Train Area

Stack

Induced Draft Fan

Combustion Air Fan

Exhaust
Gas Manifold

Oil Heater

Holo-Flite®
Processor

40   0   40   80 Ft.

Scale in Feet
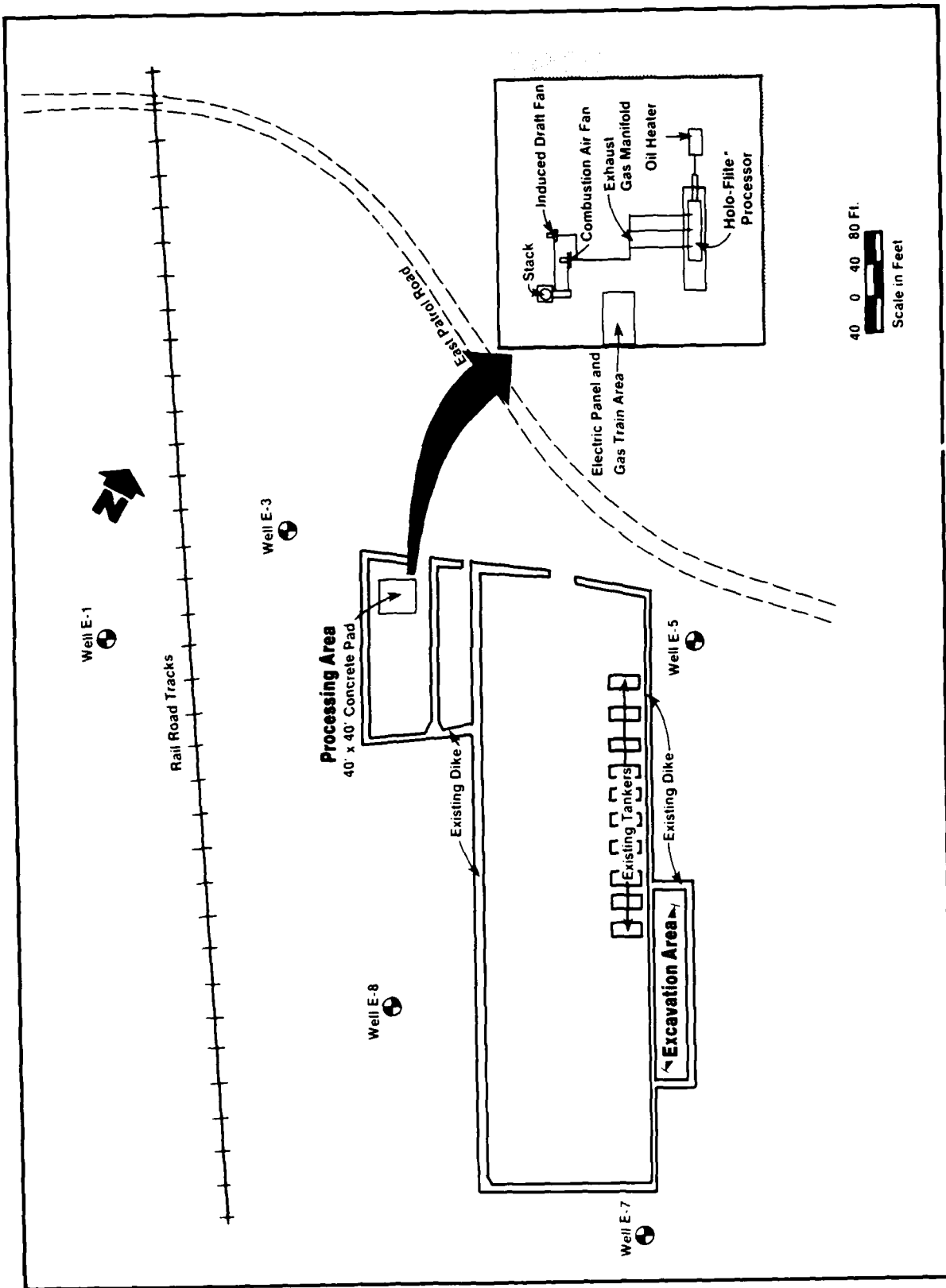
**FIGURE 3-2   LOCATION MAP OF THE PROCESSING AND
EXCAVATION AREAS ON THE LETTERKENNY ARMY DEPOT**

WESTON

FIGURE 3-3   **AERIAL PHOTOGRAPH OF THE PROCESSING AND EXCAVATION AREAS ON THE LETTERKENNY ARMY DEPOT**

State Rt. 997

Reservation boundary

349

350

351

370

320

K-4

K-1

K-3

B

K-2

A

C

G

D

E

F

I

H

J

TS-85

TS-83

TS-81

TS-84

TS-82

TS-80

Storage
tanks

Suspected contamination sources at LEAD

A. Waste disposal trenches
B. Clay-lined oil burning pit
C. Landfill
D. IWTP lagoons
E. Oil burning pit
F. IWTP ditch sludge burial spread
G. Landfill
H. Landfill
I. Landfill
J. Landfill
K-1. Lagoon
K-2. Partial revetments
K-3. Revetments
K-4. Linear magnetic anomaly
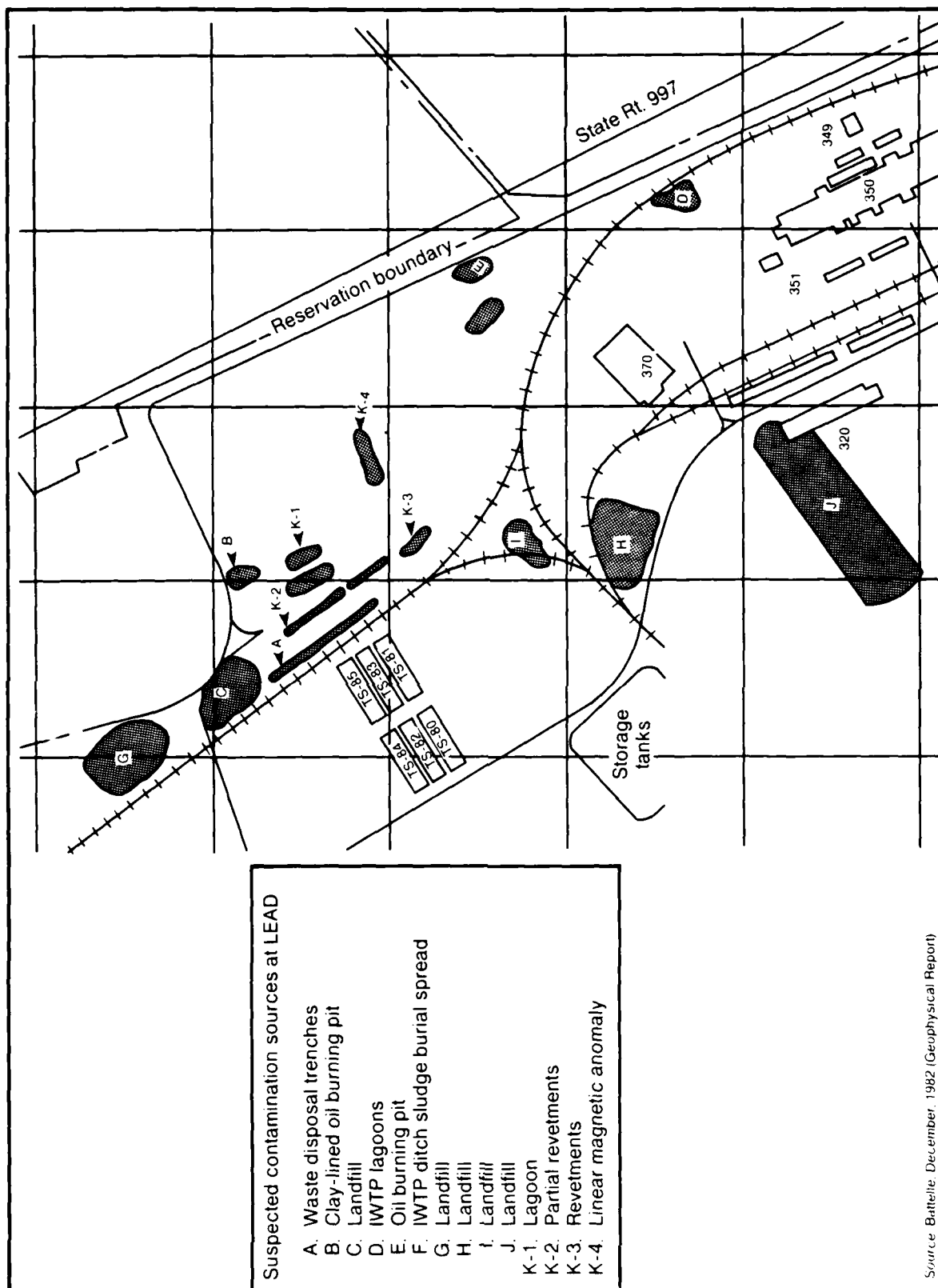
Source: Battelle December 1982 (Geophysical Report)

**FIGURE 3-4   LOCATIONS OF POTENTIAL CONTAMINANT SOURCES
EAST PATROL ROAD DISPOSAL AREA, LETTERKENNY ARMY DEPOT**

During the program, excavation trenches, excavation pits, and soil/waste borings were established on the EPRDA site in an effort to identify the vertical and horizontal extent of contamination. A 50-foot grid system was established over the seven potential waste disposal sites. At the intersection of grid lines, soil borings were drilled and samples collected at various depths from 1.5 feet to bedrock (approximately 25 feet). The field investigation determined that at least six major areas contained high levels of organic contamination and/or high levels of heavy metals. The field data further established that disposal of hazardous materials was not limited to definable areas of trenches, pits, and lagoons. Detailed organic results from the laboratory analysis of boring samples are contained in the referenced RI/FS report. For convenience, a summary table is included in Appendix A.

Based upon review of the type and extent of contamination found in the major areas, soils from Area K-1 were chosen for treatment in the pilot study. This selection was primarily based on the type, variety, concentration, and volatile nature of the compounds found in this area. Area K-1 is the site of two lagoons that were apparently used for disposal of organic liquids. The overall dimensions of the area were originally estimated to be 200 feet long by 50 feet wide, based upon a 1965 aerial photograph. The actual dimensions are not known; however, based upon trenching, the area is estimated to be at least 110 feet wide in some places. To further quantify and delineate the areas of contamination, a follow-up sampling and analysis program was completed in Area K-1 immediately prior to the pilot study.

3.2.2 Follow-up waste characterization of soils in area K-1. Based upon review of the laboratory analysis completed during the RI/FS, the soils in proximity to waste borehole 31 (WB-31), i.e., the most highly contaminated borehole, were selected for treatment in the pilot study. To further assess the lateral and vertical extent of contamination in this area, a field sampling program was conducted on 10, 11, and 12 June 1985. Eleven boreholes were drilled to a depth of 10 feet. Five composite soil samples per borehole were collected at various depths. The location of the boreholes, relative to WB-31, is

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shown in Figure 3-5. All soil samples were analyzed for those volatile organic compounds (VOC's) listed on the Hazardous Substance List (HSL). A list of the VOC's contained on the HSL, as well as their detection limits, is provided in Appendix A. A list of those compounds determined to have been present, as well as the concentration ranges, is also contained in Appendix A. For convenience, a list of major compounds found is shown, along with maximum and average concentrations, in Table 3-1.

3.3   Site/soil characteristics.

3.3.1   Site characteristics. As stated in Subsection 3.2.1, Area K-1 is the site of two lagoons that were allegedly used for the disposal of organic liquids, as evidenced by the high concentrations of organic contaminants found in the soil. However, excavation operations conducted during the pilot study indicated that a wide variety of miscellaneous debris was also deposited at this site. Typically, at a depth of approximately 3 to 5 feet an assortment of miscellaneous objects were unearthed; i.e., brake drums, wire, bolts, metal washers, bottles, shell casings, rubble, and trash. In addition, based upon the recommendation of various LEAD personnel, late in the program site soils were tested for asbestos. Test analyses confirmed the presence of low levels of asbestos, probably due to past disposal practices.

3.3.2   Soil characteristics.   The soil series for Area K-1 are classified as Urban Land. According to the Soil Conservation Service (SCS) of Franklin County, Pennsylvania, urban land is land that is so altered that identification of soils is not feasible. Included in this classification are areas that have been cut and filled with earthy and trashy material. This series generally consists of nearly level to sloping land that has been affected by urban development. Included in this unit are soils that have been cut and filled with earth and trash material.

Excavations in Area K-1 during the pilot study indicated that a gravelly sandy silt fill covered the surface to an approximate depth of 2 feet. From two to five feet below ground surface, miscellaneous fill material consisting of gray silty clay with sand, gravel, black ash, and metallic debris was encountered. Native soils varying from orange, brown sandy, gravelly plastic clays to slightly plastic clayey silts were generally observed between 5 to 7 feet. In addition, a perched water table was occasionally observed at the interface of the native soil and fill.

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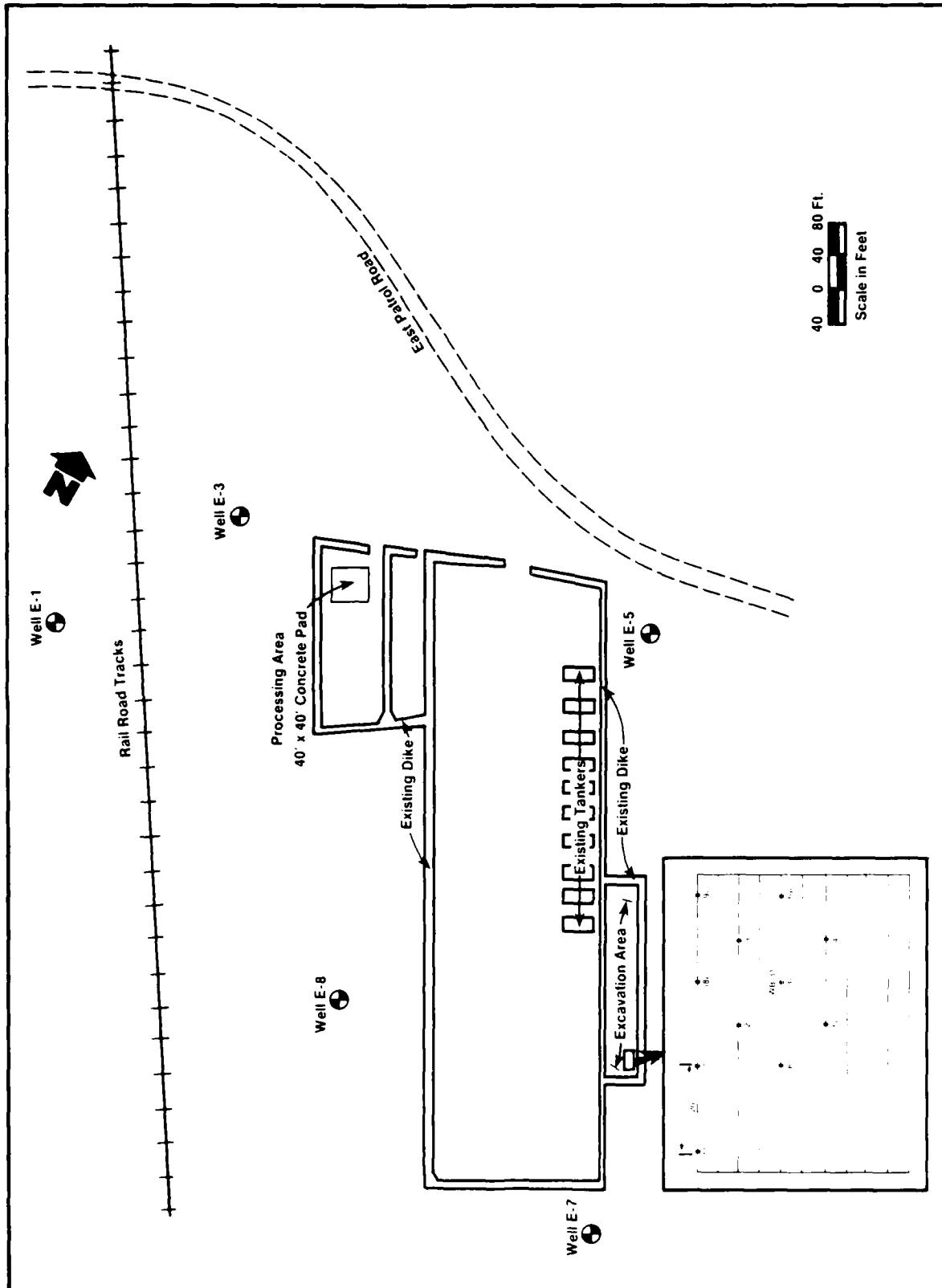
FIGURE 3-5 LOCATION OF SOIL BORINGS DRILLED IN AREA K-1 DURING
THE WASTE CHARACTERIZATION PHASE OF THE PILOT STUDY

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TABLE 3-1.   CONCENTRATION RANGE OF VOC'S DETERMINED TO BE
             PRESENT IN AREA K-1 (BASED ON TESTING PERFORMED
             ON 10, 11, 12 JUNE 1985)

Volatile organic compound	Average concentration (ppm)	Maximum concentration (ppm)
1,2-Trans Dichloroethylene	115	>1,300
Trichloroethylene	222	>3,500
Tetrachloroethylene	95	>3,800
Xylene	7	47
Other VOC's (i.e., Chlorobenzene, ethylbenzene, Methylene Chloride, Toluene, Vinyl Chloride, C10-allyl Benzene, Dichlorobenzene, Methyl ethyl benzene, n-propylbenzene, Trimethyl benzene)	7	600

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Previous soil borings conducted at Area K-1 Site indicated that these native fine-grained soils extended to a depth of approximately 22 to 27 feet below ground surface, where bedrock was encountered.

Two soil samples (fill, native soil) representative of soil types treated utilizing the low temperature thermal stripping technology were retained for sieve and hydrometer grain size analysis. Results of grain size analysis indicate the fill material consists of gravelly sands, and the native soil consists of sandy clay/sandy silt. These results are consistent with field observations documented during this study. Plotted grain size gradation curves for these two soil samples are retained in Appendix B of this report.

3.4 Environmental permitting. In the early stages of program development, representatives from USATHAMA and WESTON met with representatives from the U.S. Environmental Protection Agency (EPA) Region III and the Pennsylvania Department of Environmental Resources (PADER). At that time, background information concerning development of the thermal stripping process, selection of LEAD as the testing site, and technical details of the process and equipment were presented to the agencies for review. The point was emphasized that the pilot study was a generic research program and in no way a specific remedial action project for LEAD. The three areas that were identifed as having a potential environmental impact were air emissions, processed soil, and decontamination water.

3.4.1 Air emissions. The main area of concern in the pilot study centered on the issue of air emissions. The proposed process design included treatment of the off-gases in an afterburner operating at a minimum temperature of 1,000°C (1,832°F) and a residence time of greater than 2 seconds.

Theoretically, the proposed afterburner system would be sufficient to affect the thermal destruction of the VOC's in the off-gases. However, to demonstrate the efficiency of the afterburner the agencies agreed that stack gas sampling would be conducted at a selected low, medium, and high VOC-inlet loading condition. PADER was subsequently supplied with a copy of the test plan[4] describing the proposed test runs, detailed technical aspects of the process equipment, and proposed sampling methods.

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The test plan was reviewed by the Air Quality Control Section of PADER. Upon review, PADER raised no objections to the execution of the pilot investigation. In view of the relatively short duration of the pilot study, PADER determined that the process was exempt from permitting requirements.

3.4.2   Disposal of the processed soils. Originally, the test plan submitted to PADER dictated disposal of the processed soils in a licensed hazardous waste disposal facility. However, upon review of the test plan, the Solid Waste Management Section of PADER granted approval to redeposit the processed soils at the excavation area from which they were originally removed. The basis for this decision was twofold. First, the U.S. Army will be completing full scale cleanup measures in the future. This remedial action will address all site soils. Second, the thermal stripping process does not render the processed soil more hazardous than the soil in its original state. In fact, application of this technology should result in reduced concentrations of VOC's.

3.4.3   Disposal of the decontamination water. Originally, the water generated during decontamination of personnel and equipment was to be collected for proper disposal at the LEAD industrial wastewater treatment plant. However, the Solid Waste Management Section of PADER granted approval to redeposit the decontamination water at the excavation and processing site. The primary reason for approval was that all site soils will be addressed in future remedial actions.

4. DESCRIPTION OF THE PROCESS EQUIPMENT

The concept of low temperature thermal stripping essentially couples two removal mechanisms:

(a) Removal by thermal volatization, and
(b) Removal by aeration.

To determine the singular effect of these removal mechanisms, two types of equipment were used for the pilot study:

(a) A thermal processor to determine the effects of thermal volatization, and
(b) An aeration unit to evaluate the aeration effects.

The thermal processor was a pilot-scale piece of equipment that was able to continuously process from 100 to 265 pounds of soil per hour, depending on soil residence times. Test conditions were varied using the thermal processor, and an extensive soil and air sampling program was completed. The aeration unit, on the other hand, was strictly a bench-scale piece of equipment able only to process a batch of 10 pounds of soil per test. A less rigorous testing and sampling program was conducted on the aeration unit. As such, an "apples-to-apples" comparison of the two pieces of equipment is not valid since the evaluation of each unit was not equal. Therefore, the aeration unit will be evaluated as a bench-scale investigation in a separate report. This document will evaluate only the pilot-scale thermal processor.

4.1 <u>Thermal processing system</u>. The thermal processor is an indirect heat exchanger which is commonly used to heat, cool, or dry bulk solids, slurries, pastes, or viscous liquids. In the pilot test application, the thermal processor was used to heat and consequently dry contaminated soil. The net effect of heating the soil was to evaporate volatile contaminants from the soil. A carrier gas (i.e., air) was introduced to the unit to enhance contaminant removal. An illustration of the thermal processing system is presented in Figure 4-1. A description of each component of the thermal stripping process is contained in the following subsections.

4.1.1 <u>Feed soil system</u>. Depending upon the desired soil residence time, the soil feed rate varied throughout the pilot investigation. However, the cycle feed rate (i.e., weight of soil per loading cycle) remained constant. Approximately 10 pounds of soil per loading cycle were fed to the unit at regular intervals. An air-tight rotary valve mechanism was used to introduce soil to the thermal processor. A schematic of the feed soil system is shown in Figure 4-2.

4-1

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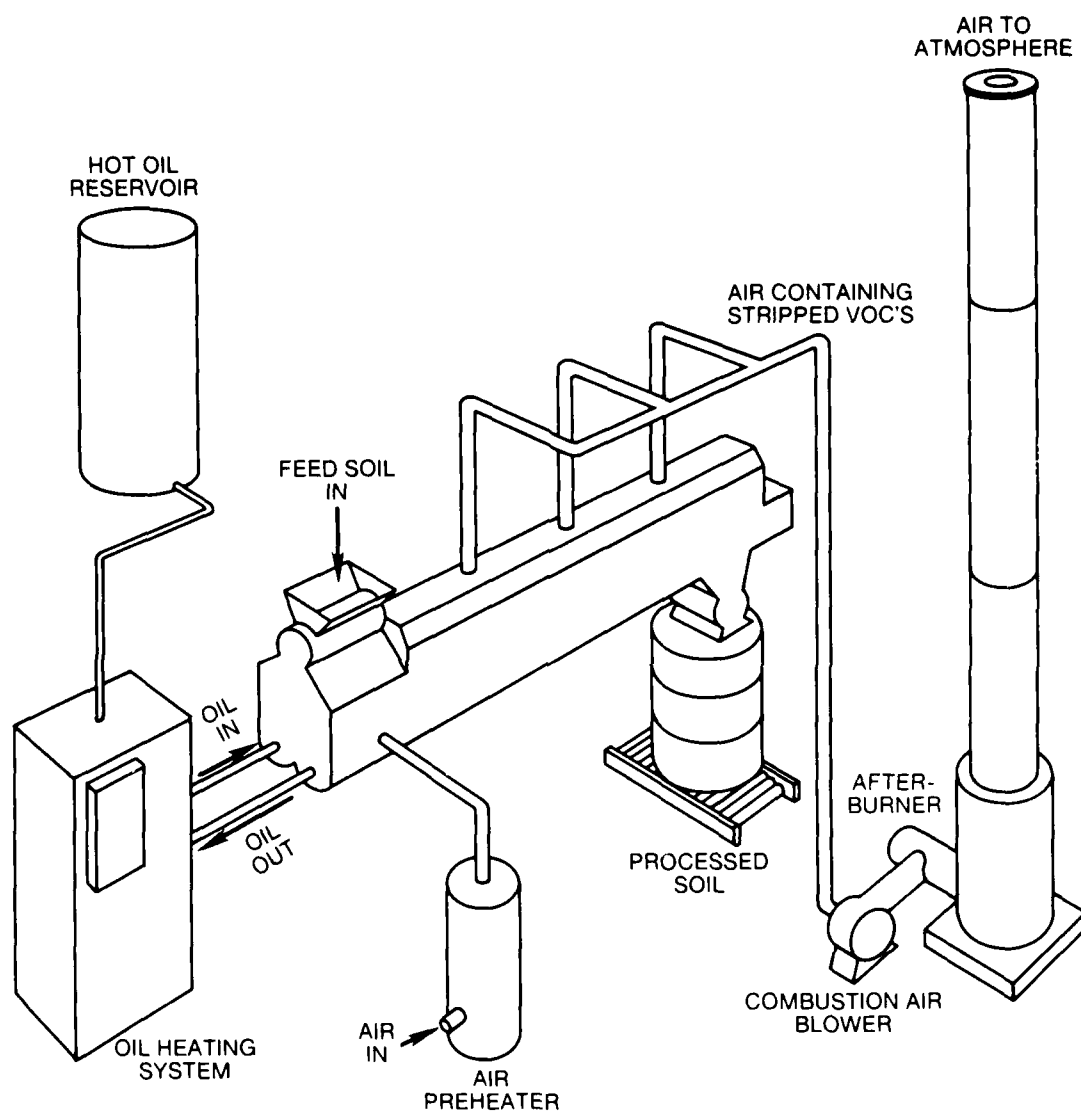
Figure 4-1.   Thermal processing system.

Hopper

Lid

Air Lock

Soil
to Processor
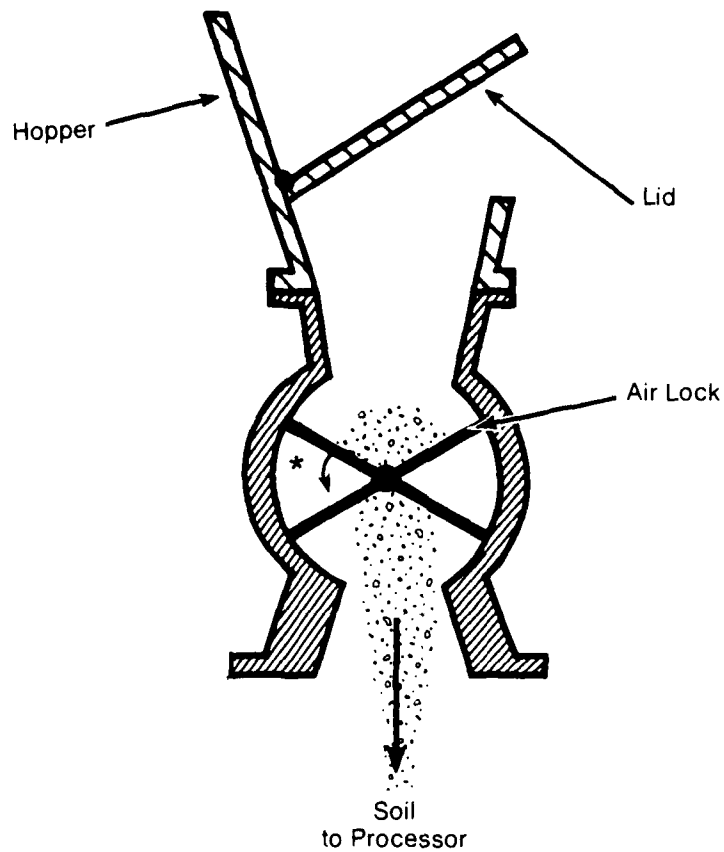
*Note: During each feed cycle the rotary valve would
rotate 180° in the direction shown.

FIGURE 4-2   SCHEMATIC OF ROTARY VALVE FEED MECHANISM

The rotary valve assembly was housed in a feed hopper that was equipped with a safety latch. The valve was not operational unless the hopper lid was in the closed position. The soil was loaded into an empty cavity of the rotary valve. As required, the loading operator manually activated the valve switch. The valve slowly rotated 180°, discharging the soil into the front end of the processor. As the rotary valve was of symmetrical construction (two of the six vanes were removed to facilitate feeding), upon rotation an empty cavity was positioned in the upright position, ready for the next loading cycle.

As shown in Figure 4-2, the vanes of the valve maintained a constant air lock, even during rotation. This air lock was used to prevent air from being drawn into the system and fugitive emissions from escaping into the atmosphere. Fugitive emissions were further prevented by constantly maintaining a negative pressure within the thermal processor.

4.1.2 Thermal processor. The thermal processor consisted of a jacketed trough which housed a double-screw mechanism. The Holo-Flite[R] screws were seven inches in diameter and ran the entire length of the trough. The screw shafts and flights were hollow to accommodate circulation of the heat transfer liquid (i.e., hot oil). The oil flowed through the flights in a direction cocurrent to the movement of the soil. The oil entered the unit at the soil feed end of the processor, circulated through the flights, and flowed back through the shaft to exit the unit at the same end that it entered. An internal view of the thermal processor is shown in Figure 4-3.

The trough jacket also circulated hot oil, providing additional heat exchange with the soils being processed. The side clearance between the screws and the trough was 1/2-inch and the bottom clearance was 3/4-inch. The screws were driven at various rotational speeds via a chain drive connected to the gear reducer located beneath the conveyor. The continuous action of the screws promoted forward movement of the soil through the trough. The screws were set in the trough so that the flights of the two screws meshed with each other to break up the soil and improve heat transfer.

The area above the twin screws was covered by a hood as shown in Figure 4-3. The hood was equipped with three vertical plates that extended from the top of the hood to within a small clearance of the twin screws. The plates separated the head space in the unit into three equally sized sections. One air exhaust port was connected to each section to facilitate removal of vapors via three exhaust lines.

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Shaft

Flight

Air Discharge
Port

Hood

FIGURE 4-3   INTERNAL VIEW OF THERMAL PROCESSOR

The processsor used during the evaluation was a pilot-scale unit; larger units are available. Full-scale processors are equipped with a variety of options. Four screw sizes are available (i.e., 7-, 12-, 16-, and 24-inch diameter). The screws vary in length from 10 feet to 24 feet, depending on the screw diameter. The processor is fabricated with either one, two, or four screws per unit. A variety of drive arrangements are available to alter the screw speed to meet individual requirements.

Although various screw and trough arrangements are available, the side and bottom clearances between the flights and trough remain fixed at 1/2-inch and 3/4-inch, respectively, regardless of screw size. If jamming problems are anticipated and larger clearances are required, the unit must be specially fabricated (i.e., flights are machined down to the desired diameter). For informational purposes, no jamming problems were encountered with the screws and trough during the pilot study. Efforts were made to screen out large objects; however, occasionally oversized items were inadvertently fed to the processor and exhibited no adverse effects (with the screws and trough). Also, during a dry run with uncontaminated soil, the hood was allowed to remain open, and the operation of the unit was observed. Large objects, purposely fed to the unit, merely straddled the top of the flights. No jamming problems were experienced.

4.1.3 Processed soil handling system. The discharge end of the Holo-Flite[R] processor incorporated an air-tight rotary valve mechanism, similar to that used in the feed system. For illustration, a photograph of the soil discharge gate is shown in Figure 4-4. The valve mechanism was motor-driven and was in continuous operation while the screws were rotating. The air lock sealed the unit from air infiltration and prevented excessive dust generation inherent in the dry processed soil.

The continuous discharge of soil was collected in open top 55-gallon drums. A fabric shroud and sealing band around the top of the processed soil drum minimized fugitive dust emissions. The drums were situated on a roller conveyor to facilitate their removal and replacement.

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Fabric
Shroud

Rotary
Valve
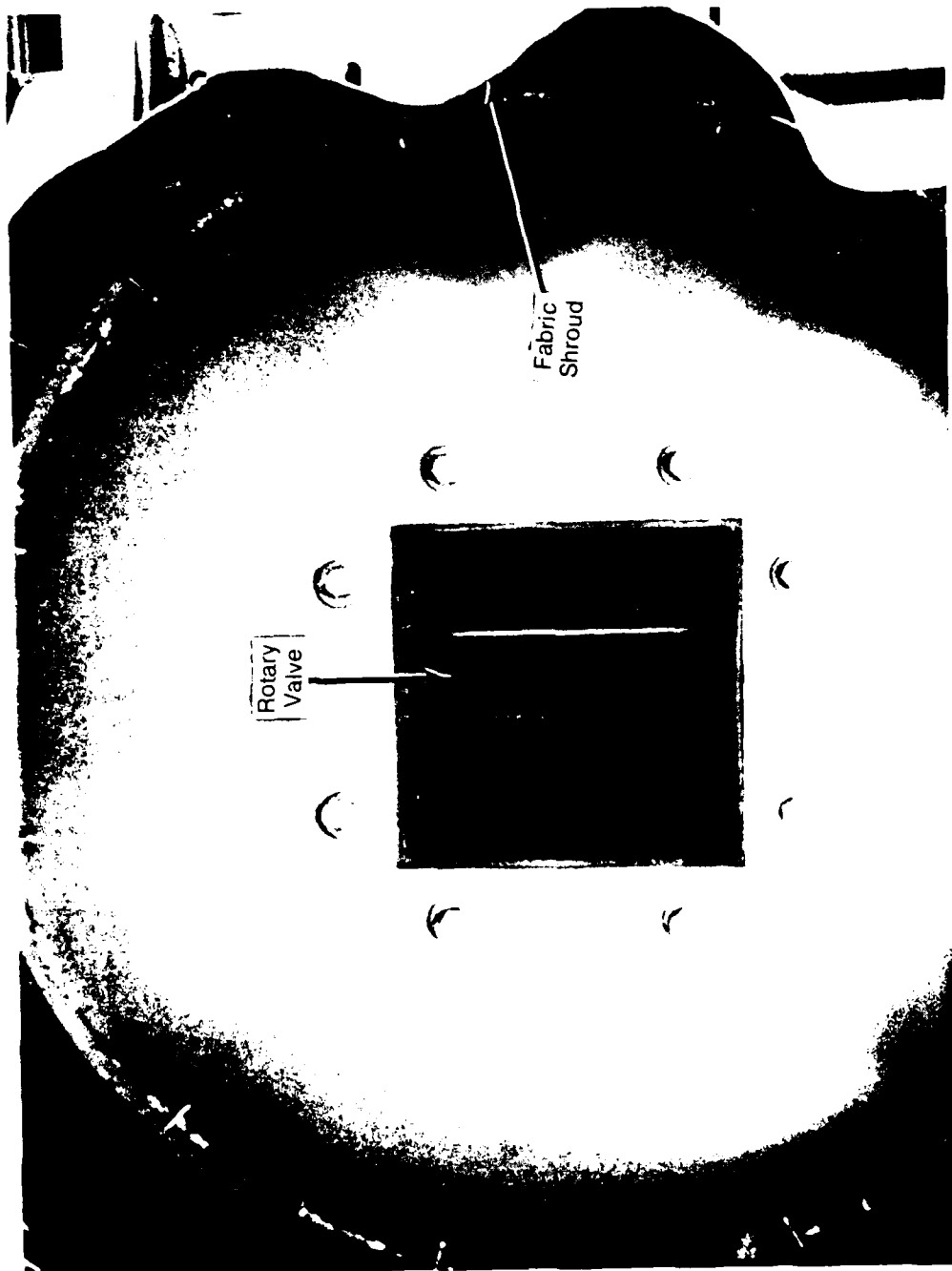
FIGURE 4-4 SOIL DISCHARGE GATE

WESTON

4.1.4 Hot oil system. The source of heating fluid for the thermal processor was a Chromalox Type COS Hot Oil Heat Transfer System: Model COSX-650-80, rated at 80 kilowatts at 480 volts. The heat exchange fluid was Monsanto Therminol 66, which had a temperature range of ambient to 315°C (600°F).

The system was self-contained and consisted of an oil reservoir, heater element system, temperature control system, expansion tank, high temperature pump, controls, and steel housing.

The hot oil for a given test was delivered via piping and valving to each of the Holo-Flite[R] screws and subsequently to the thermal processor trough.

4.1.5 Air systems. A carrier gas (i.e., air) was circulated through the unit to enhance contaminant removal. The air passed through a preheater and entered the thermal processor at a controlled temperature. Once inside, the air stream was forced to travel a tortuous path by flowing through the divided sections of the processor. Off-gases were removed through three ports located in the hood of the processor, as shown in Figure 4-5. The three-leg manifold combined into a main header. An induced draft fan was located downstream of the header and provided the motive power to induce air flow through the system. A brief description of the individual components of the air system is contained in the following subsections.

4.1.5.1 Air inlet system.

4.1.5.1.1 Air preheater. A Chromalox Process Heater (Model GCH-60905-E4) was used to raise the temperature of the process air during selected test runs. The electrical resistance heater was rated at 9 kilowatts at 480 volts. It was equipped with a temperature control system that enabled the temperature of the air to be heated from ambient to approximately 90°C (200"F).

4.1.5.2 Off-gas system.

4.1.5.2.1 Air manifold system. The gases generated and drawn through the thermal processor were removed through the three ports located in the hood. Each leg of the manifold system contained an air orifice for balancing air flows as well as individual ports for off-gas sampling. The manifolds fed into a main header which had its own test port. The main header was ducted to the entry of the induced draft fan.

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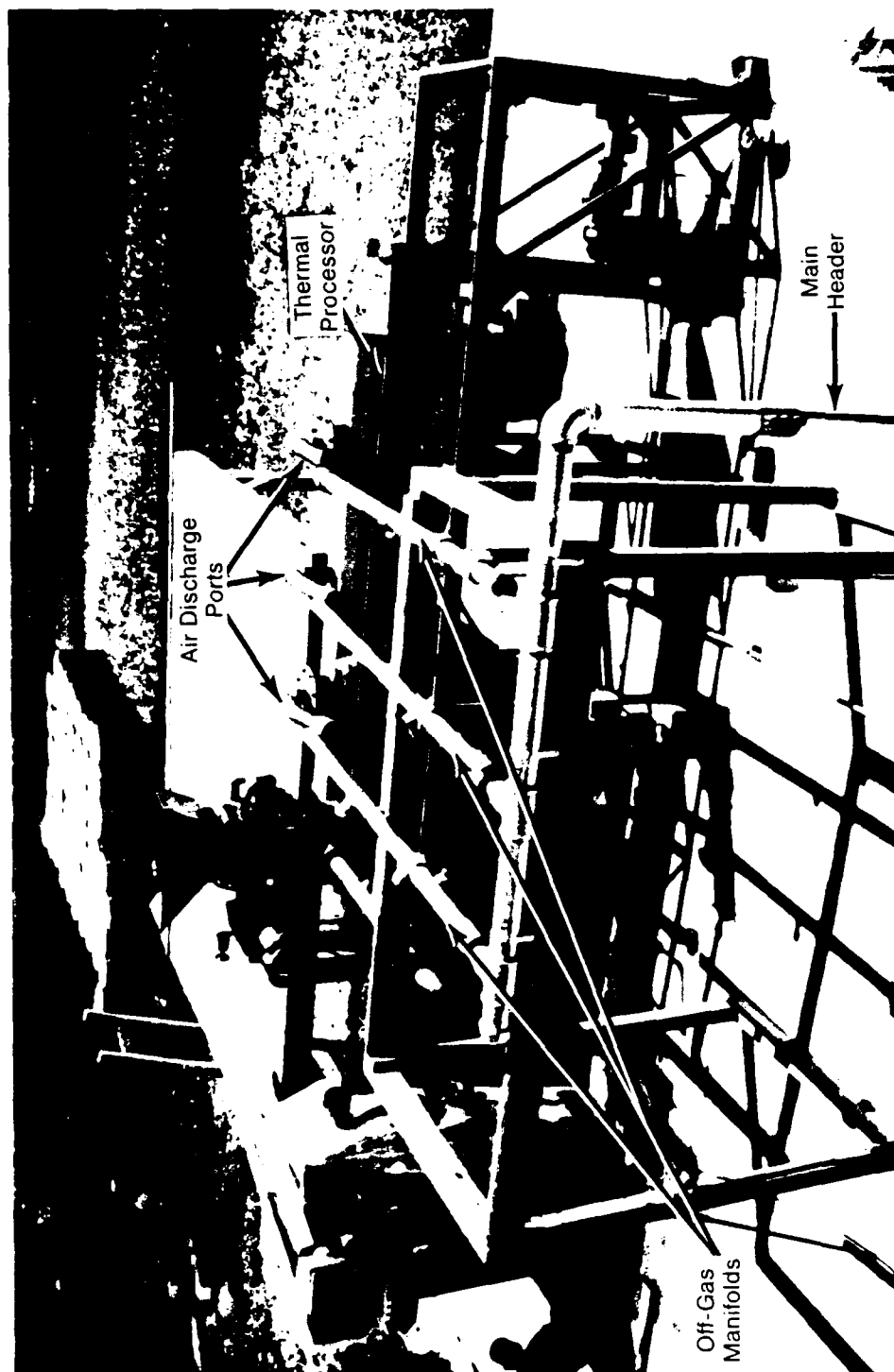
FIGURE 4-5   OFF-GAS DISCHARGE LINES

4.1.5.2.2 Damper. The main header contained a damper to regulate the flow of air through the thermal processor. In the fully open position, approximately 200 dry standard cubic feet per minute (dscfm) of air flowed through the system. The minimum air flow, corresponding to a nearly closed position, was approximately 75 dscfm.

4.1.5.2.3 Induced draft fan. An induced draft fan was located downstream of the manifold system. It provided the motive power to induce air flow through the system. The discharge of the fan was fed directly into the afterburner and served as combustion air.

4.1.6 Emission control system.

4.1.6.1 Afterburner. The afterburner operated at a minimum temperature of 1,000°C (1,832°F) and a residence time of greater than two seconds. The afterburner was propane-fired using a North American burner rated at 1.5 x 10 million British thermal units per hour (Btu/hr). Safety controls on the burner included a combustion air pressure switch, gas low pressure switch, gas high pressure switch, burner safety control system, low fire switch, and ultraviolet (UV) flame safety.

4.1.6.2 Refractory-lined stack. The refractory-lined stack was 18 inches in diameter and 20 feet high. It housed two thermocouples: the first for controlling burner temperature and the second for a system high temperature alarm.

4.1.6.3 Propane System. Two propane tanks were available to provide fuel for thermal destruction of the VOC's. The propane was piped directly from the tanks to the gas train of the afterburner system.

4.1.7 Electrical supply. A diesel-fired generator supplied electrical power during the pilot investigation. The generator was rated at 250 kilowatts and supplied 115/480 volt power to the process equipment.

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5. PILOT STUDY FRAMEWORK

The pilot study was completed in two phases. Phase I consisted of 18 test runs completed to evaluate the effect on VOC removal efficiency by varying the following operating conditions:

(a) Soil discharge temperature,
(b) Soil residence time, and
(c) Air inlet temperature.

The 18 "base case" test runs were designed in a matrix format to investigate three levels of soil discharge temperature: 50°C, 100°C and 150°C; three levels of soil residence time: 30 minutes, 45 minutes, and 60 minutes; and two levels of air inlet temperature: ambient and 90°C. Phase I test runs were conducted from 5 August 1985 through 26 August 1985.

Upon completion of Phase I of the pilot study, an additional 10 "optimization" runs were completed as Phase II of the pilot investigation. The purpose of the optimization test runs was fourfold:

(a) Test Runs 19, 20, 21 - To evaluate the effects on VOC removal efficiency by extending the soil residence time and soil discharge temperature to values beyond those investigated in Phase I of the pilot study, i.e., 75 and 90 minutes and maximum soil discharge temperature. Also, to monitor the discharge air in the three legs of the manifold system to determine the contaminant removal trends.

(b) Test Runs 22, 23 - To evaluate the effects on VOC removal efficiency by extending the soil residence time while maintaining a soil discharge temperature that was evaluated in Phase I of the Pilot Study, i.e., 150°C. Also, to monitor the discharge air in each leg of the manifold system to determine the contaminant removal rates.

(c) Test Runs 24, 25, 26 - To evaluate the "reproducibility" of treatment associated with three test runs with exact "steady state" conditions, i.e., fixed soil residence time, soil discharge temperature, and air inlet temperature.

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(d) Test Runs 27, 28 - To evaluate the VOC removal efficiency associated with "reprocessing" soils that were already processed but, due to operating conditions that were less than optimum, still contain a VOC contaminant residual.

Phase II test runs were conducted from 27 August 1985 through 16 September 1985. Table 5-1 provides a schedule of the test run dates for both phases of the study, as well as the process variables that were controlled during each test run. The schedule of test runs, as well as the corresponding operating conditions, are listed in Table 5-1.

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TABLE 5-1. SUMMARY OF TEST RUN MATRICES AND CONTROLLED TEST
VARIABLES - PHASE I AND PHASE II TEST RUNS

Test run	Test run date	Matrix no.	Target soil resi- dence time (minutes)	Target soil discharge temper- ature (°C)	Target air inlet temper- ature (°C)
A.	**Phase I - Base Case Test Runs**				
8	8/13/85	1-1	30	50	ambient
16	8/23/85	1-2	30	100	ambient
15	8/21/85	1-3	30	150	ambient
3	8/7/85	1-4	45	50	ambient
6	8/10/85	1-5	45	100	ambient
14	8/20/85	1-6	45	150	ambient
1	8/5/85	1-7	60	50	ambient
17*	8/24/85	1-8	60	100	ambient
13	8/19/85	1-9	60	150	ambient
7	8/12/85	2-1	30	50	90
9	8/14/85	2-2	30	100	90
12*	8/17/85	2-3	30	150	90
18	8/26/85	2-4	45	50	90
4	8/8/85	2-5	45	100	90
11	8/16/85	2-6	45	150	90
2	8/6/85	2-7	60	50	90
5	8/9/85	2-8	60	100	90
10	8/15/85	2-9	60	150	90

*Used soils from previous day's excavation.

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TABLE 5-1
(continued)

Test run	Test run date	Matrix no.	Target soil residence time (minutes)	Target soil temperature (°C)	Target air inlet temperature (°C)
B.	Phase II - Optimization Test Runs				
19	8/27/85	–	60	210	90
20*	8/28/85	–	90	210	90
21	8/29/85	–	75	210	90
22	9/4/85	–	60	150	90
23*	9/5/85	–	90	150	90
24	9/12/85	–	60	50	ambient
25*	9/13/85	–	60	50	ambient
26*	9/14/85	–	60	50	ambient
27	9/15/85	–	60	max	ambient
28	9/16/85	–	90	max	ambient

*Used soils from previous day's excavation.

6. TYPICAL ON-SITE ACTIVITIES

On 22 July 1985 Canavan Technologies, Inc., the equipment subcontractor, began installation of the process equipment. The pilot-scale thermal processor, as well as support equipment and piping, was delivered to the test site on a single flat bed truck. Installation was completed and the entire system was fully operational in ten days. The official testing program began on 5 August 1985 and continued through 16 September 1985. A description of the typical daily routine, as well as project closure activities, is contained in the following subsections. For illustration, the daily schedule of on-site activities is presented in Figure 6-1.

6.1 **Daily routine**. Typically, the regular test crew consisted of the following personnel:

(a) Site engineer (1).
(b) Process equipment operator (1).
(c) Safety officer (1).
(d) Excavation technicians (2).
(e) Materials handling technician (1).
(f) Air sampling technicians (2).
(g) Backhoe operators (2).

Under special circumstances (e.g., stack sampling), additional personnel were required on site.

6.1.1 Pretest activities.

6.1.1.1 Equipment startup and stabilization. Each morning at approximately 6:30 a.m., the process equipment operator arrived on site for equipment startup and stabilization. To comply with the adopted safety protocol (i.e., a minimum of two persons required on site at all times) the backhoe operators arrived simultaneously. The equipment operator cleaned the UV sensor and spark plug prior to igniting the afterburner. The afterburner temperature was gradually brought up to 1,800°F. Depending upon the selected test run conditions for the thermal processor, the equipment operator gradually increased the oil temperature to the appropriate setpoint.

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Time of Day (Hours)

Activity
Process equipment operator and backhoe operators arrive on-site
Equipment start-up and stabilization
Test crew arrives on-site
Prepare sample bottles
Excavation activities
Instrument evaluation
Begin feed soil to unit
Prepare sampling test equipment
Conduct formal test and monitor thermal processor during "steady state" conditions
Recover samples
Equipment shutdown
Secure area
Operators and test crew leave site

Time axis: 0600 0700 0800 0900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000

FIGURE 6-1   TYPICAL SCHEDULE OF DAILY ON-SITE ACTIVITIES

If the test run conditions called for preheated air, the equipment operator set the air heater to the maximum setpoint (i.e., 90°C). To accommodate the desired soil residence time, the speed of the screws was adjusted to the appropriate setpoint. Also, as a routine practice, the orifice plates in the three off-gas manifolds were removed and cleaned prior to introducing soil to the unit.

6.1.1.2 Excavation activities. The site engineer, safety officer, and excavation team normally arrived on site at 7:00 a.m. to commence excavation activities. The first order of business was "suiting up" to enter the designated "hot zone." All personnel involved in activities in the hot zone were required to wear level C safety gear. This included disposable Saranex® coveralls, steel toe/steel shank boots, surgical under gloves, neoprene outer gloves (duct taped to the coveralls), outer booties (duct taped to the coveralls), hardhats and full-face respirators equipped with cartridges designed for VOC removal.

The backhoe operator generally began excavation between 8:00 - 8:30 a.m. In order to isolate contaminated soils, an organic volatile analyzer (OVA) was used to monitor the head space in each backhoe bucket of soil. Only those soils that exhibited a head space concentration of at least 50 parts per million (ppm) total VOC's were selected for treatment during the pilot study. Typically, *sufficiently contaminated soil* was found at a depth of 3 feet and continued through a depth of 5 to 6 feet. Once sufficient VOC concentrations were detected by the OVA, the contaminated soil was deposited in a separate pile and the teeth of the backhoe bucket were used to break up large clumps of soil.

The excavation technicians shovelled approximately 10 to 15 pounds of contaminated soil into 5-gallon capacity metal pails. Each pail was provided a metal top, equipped with a rubber seal, to inhibit fugitive emissions during storage and transportation. Typically, 100 to 120 pails were loaded daily. In order to collect a sample that was representative of the excavated soil, a scoop of soil was removed from each pail and deposited into a separate bucket designated for collection of a composite soil sample. The sample pail was stored on ice in an insulated cooler to inhibit fugitive VOC losses. The composite sample of excavated soil was used to identify and quantify the VOC's in the soil as well as to determine moisture content. The composite sample was thought to be representative of the excavated soils since a portion of soil from each pail was used during collection of the sample.

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As the pails were filled, sampled, and secured, they were loaded into the bucket of the spare backhoe (designated for use in the "cold zone"). The backhoe operator extended the bucket of the backhoe over the "hot zone" boundary to facilitate loading. Once loaded, the pails were transported to the processing area. When sufficient soil for a full day of operation was loaded into the pails, the top soil was redeposited into the trench. At the completion of excavation activities, the excavated trench dimensions were approximately 4 feet wide, 8 feet long, and 5 to 6 feet deep. After the top soil was placed in the trench and the area was regraded, the location for the next day's excavation was identified. The backhoe was normally moved 10 feet north to dig another trench, parallel to that day's excavation. If sufficient concentrations of VOC's were present in the soil head space, the trench was refilled and the backhoe remained in place for the next day's excavation. If sufficiently contaminated soil was not found, the backhoe operator would continue with exploratory trenches until "hot soil" was identified.

All personnel working in the hot zone were required to decontaminate (i.e., "decon") before exiting the designated hot zone boundaries. The decon procedure included the following chronologically ordered steps:

(a) Outer boot wash/rinse.
(b) Outer glove wash/rinse.
(c) Hardhat and respirator removal.
(d) Outer boot duct tape removal.
(e) Outer glove duct tape removal.
(f) Outer boot removal.
(g) Outer glove removal.
(h) Saranex removal.
(i) Inner glove wash/rinse.
(j) Inner glove removal.

All contaminated clothing was collected for proper disposal by LEAD.

6.1.1.3 Instrument evaluation. The air sampling technicians normally arrived on site at 7:00 a.m. to conduct an evaluation of selected instruments. The purpose of the instrument evaluation was to determine the accuracy and reliability of portable field instruments for detecting VOC's in soil. The following instruments were included in the evaluation:

(a) Century OVA.
(b) HNu 101.

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(c) AID 590 OVM/GC.
(d) Photovac TIP.

The air sampling technician monitored the head space above contaminated soils using the subject instruments. The soils used in the evaluation were the excavated and feed soils from the previous day's test run. The VOC concentrations detected by each instrument were recorded for comparison to VOC concentrations detected by laboratory obtained gas chromatograph/mass spectrometer (GC/MS) to determine if a correlation existed. A more detailed description of the instrument evaluation, as well as results and conclusions, is included in a separate report, (Report No. AMXTH-TE-CR 86073).

6.1.1.4 Materials handling.

6.1.1.4.1 Feed soil. As previously mentioned, the excavated soils were transported to the processing area in sealed pails placed in the bucket of a backhoe. The materials handling technician unloaded the pails, weighing and recording their weight. All pails were stored on the loading platform. The volume of soil in a "typical" pail was recorded, as well as its weight, to determine the feed soil density. When the process equipment (thermal processor and afterburner) was stabilized and the appropriate operating conditions were maintained, the materials handling technician began feeding contaminated soil to the thermal processing unit.

6.1.1.4.2 Processed soil. The drums of processed soil from the previous day's test run were weighed each morning. In addition, the volume occupied by the soil was recorded to determine its density.

6.1.1.5 Sampling equipment. Sample containers were prepared and labelled prior to each test run. In addition, the air sampling technicians set up the appropriate test equipment required for sample collection and monitoring.

6.1.2 Test activities. The test run was officially underway when the system was stabilized and soil was discharging from the unit at the appropriate temperature. The soils processed before the system was stabilized were collected in 55-gallon drums. When the system stabilized, the drum was removed, and an empty drum was placed at the soil discharge gate to collect soils treated under official test conditions. A brief description of test activities is included in the following subsections.

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6.1.2.1 Feeding soil to the processor. As each pail was opened, a scoop of soil was removed and deposited in a separate composite sample bucket. The sample bucket was stored on ice in an insulated cooler to inhibit fugitive emissions of VOC's. The technician filled the empty cavity of the rotary valve with soil, removing large rocks, metal objects, etc. Depending on the soil residence time, loading cycle times varied. At the appropriate time, the rotary valve switch was activated, the valve rotated 180°, and the soil was introduced to the unit. The same procedure was repeated for every loading cycle. From the beginning to the end of each formal test run, the materials handling technician sampled each pail of soil fed to the unit.

6.1.2.2 Air sampling activities. Air monitoring and sampling of the thermal treatment system off-gases were conducted during the formal test run. Sampling equipment was installed at the following locations during appropriate test runs to monitor parameters:

(a) Air temperatures (processor inlet, off-gas manifold, afterburner inlet, discharge stack);
(b) Air flow rates (processor inlet, off-gas manifold, afterburner inlet, discharge stack);
(c) Gross VOC concentrations (processor inlet, off-gas manifold, afterburner inlet);
(d) Specific VOC concentrations (off-gas manifold, afterburner inlet discharge stack); and
(e) Moisture content (afterburner inlet discharge stack).

A description of parameters, sampling techniques, and analytical methods are included in Section 7.

6.1.2.3 Processed soils. At the beginning of each formal test run, an empty drum was placed at the soil discharge gate to receive the treated soils. Sampling devices were placed in the drums to collect composite samples of the processed soils. Two members of the excavation team monitored the level of soil in the drum, changed the drum as required, and regularly monitored the soil discharge temperature.

6.1.3 Post-test activities. The formal test run usually lasted for 2 to 3 hours. Depending upon weather conditions and equipment upsets, some test runs were of shorter duration. A brief description of activities that occurred upon completion of the test run is included in the following subsections.

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6.1.3.1 Equipment shutdown. The materials handling technician introduced approximately 100 pounds of coarse sand to the processor to purge the system of residual soil. Simultaneously, the equipment operator decreased the temperature control settings on the afterburner, oil heater, and, as required, process air heater.

6.1.3.2 Sample collection. The composite samples of the excavated, feed, and processed soils were split into the appropriate sample bottles. Forty-milliliter volatile organic analysis (VOA) bottles were filled with each soil type for analysis by GC/MS. As a precaution, duplicate samples were retrieved. In addition, five 100-milliliter bottles were filled with each type of soil for analysis by the field instruments used in the instrument evaluation phase of the program.

6.1.3.3 Securing the area. At the end of each day, the entire processing area was rinsed down using a high pressure water sprayer. When the process equipment was cooled down to the appropriate temperatures, the diesel generator was shut down and all personnel evacuated the site.

6.1.4 Miscellaneous activities. Twice a week a runner picked up the samples as well as chain-of-custody forms for delivery to the WESTON Laboratory in Lionville, Pennsylvania.

6.2 Project closure activities.

6.2.1 Excavation area. As discussed in Subsections 3.4 and 3.4.1, PADER approved backfilling of processed soils in the excavation area. A backhoe was used to excavate a trench, 4 feet deep, 4 feet wide, and approximately 40 feet long. The processed soil drums were tipped over and the soils were dumped into the trench. As the processed soils were extremely dry, dust generation was likely. To minimize dust production, the LEAD Fire Department was on site during the dumping operation. A water tanker was used to supply a fine mist of water over the trenched area. The entire excavation area was regraded and the berm fully restored upon completion of the pilot study.

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6.2.2 Processing area.

6.2.2.1 Equipment removal. As previously mentioned, low levels of asbestos were determined to be present in some soils selected for treatment in the pilot study. The processing equipment was purged of residual soil; however, as a precaution, the equipment was decontaminated according to government regulations on asbestos. A copy of the specific regulations is included in Appendix D. (Chapter 27, Occupational Safety and Health Administration (OSHA) 29 CFR 1910.1001 and Chapter 1, EPA 40 CFR Part 61, Subpart B).

Process equipment decontamination was completed by American Asbestos Control Company. A tent was built around the processor and associated piping. All surfaces of the equipment and piping were vacuumed through a high-efficiency particulate air (HEPA) filter, wire brushed, and washed down according to regulations. All materials generated during the decontamination were bagged, placed in 55-gallon drums, and labeled "Asbestos." LEAD transported and disposed of the materials. Upon completion of the pilot study, processing equipment and all support materials were removed from the test site.

The backhoes and miscellaneous equipment were decontaminated using detergent, scrub brushes, and a high-pressure water sprayer.

Wastewaters from the decontamination of equipment were not collected for disposal. Based on the approval of the Solid Waste Section of PADER (as discussed in Subsection 3.4.3), decontamination waters were disposed of in the processing area.

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7. EXPERIMENTAL VARIABLES

The variables of the pilot study were classified as follows:

(a) Independent variables: those variables impractical to control and allowed to vary randomly throughout the tests. No attempts were made to modify or control independent variables.

(b) Control variables: those variables with values selected and maintained during test operations.

(c) Response variables: those variables with values that were a function of the selected operating conditions.

Table 7-1 provides a summary of test variables associated with the thermal processor. A brief discussion of the variables is included in the following subsections.

7.1 <u>Independent variables</u>. As shown in Table 7-1, there were two independent variables associated with the pilot study system. These independent variables were the soil feed composition/conditions (i.e., VOC concentrations, moisture content and temperature) and the air inlet composition/ conditions (i.e., VOC concentrations, moisture content, and ambient temperature).

7.1.1 Feed soil composition/conditions. One goal of the pilot investigation was to determine the capability of the system to treat actual contaminated soils. Therefore, the composition/conditions of the soils in Area K-1 were not altered prior to being introduced to the processor.

7.1.1.1 Volatile organic concentrations. As demonstrated by previous sampling programs, the variety of volatile organic compounds and associated concentations in the soils varied with location, depth, and soil type. Composite samples were collected at the excavation site, as pails were being filled, and at the processing site as soil was being fed to the unit. The composite soil samples were collected at two separate times and locations in order to estimate the amount of VOC's that escaped in the form of fugitive emissions.

7.1.1.2 Moisture content. The moisture content of the site soils was a function of local weather conditions and adsorption properties of the soil.

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TABLE 7-1. SUMMARY OF TEST VARIABLES FOR THE
THERMAL PROCESSOR

A. INDEPENDENT VARIABLES

Feed Soil Composition/Conditions

- VOC Concentrations
- Moisture Content
- Temperature

Air Inlet Composition/Conditions

- VOC Concentrations
- Moisture Content
- Ambient Temperature

B. CONTROL VARIABLES

Held Constant At All Levels

- Soil Excavation
- Soil Preparation
- Soil Discharge Handling
- Air Flow Rate

Held Constant At Various Levels

- Soil Discharge Temperature/Heating Oil Conditions
- Soil Residence Time
- Air Temperature at Inlet
- Feed Soil Rate

C. RESPONSE VARIABLES MEASURED

Processed Soil Composition/Conditions

- VOC Concentrations
- Moisture Content
- Mass Flow Rate

Air Discharge Composition/Conditions

- VOC Concentrations
- Moisture Content
- Temperature

7-2

7.1.1.3 Temperature. Feed soils were excavated and stored in sealed metal containers at the processing area. The temperature of the feed soil varied with ambient conditions.

7.1.2 Air inlet composition/conditions.

7.1.2.1 Volatile organic concentrations. Various operations involving the contaminated soils (i.e., feeding the unit, monitoring the soil discharge temperature, etc.) took place during process unit operations. Therefore, the potential existed for trace concentrations of fugitive VOC's to be present in the influent air stream. Routine monitoring for gross VOC concentrations in the ambient air was conducted over test runs.

7.1.2.2 Moisture content. The moisture content of the air stream varied with local weather conditions, time of day, etc. The moisture content was regularly monitored during test operations.

7.1.2.3 Ambient temperature. The temperature of the ambient air varied with the local weather conditions, time of day, etc. The ambient temperature was routinely monitored.

7.2 Control variables. A schedule of test runs is presented, as well as the corresponding control variables, in Table 5-1.

7.2.1 Control variables held constant at all levels. As shown in Table 7-1, there were four control variables which were held constant at all times during the pilot study. These control variables were the soil excavation, soil preparation, soil discharge handling, and air flow rate.

7.2.1.1 Soil excavation. A backhoe was used to excavate the soils. In order to locate highly contaminated soils, an OVA was used during the excavation. The OVA was used as a screening tool to ensure that soils contained detectable levels of volatile organic compounds to be processed. Typically soils containing at least 50 ppm total VOC's were selected for treatment. Approximately 10 to 15 pounds of soil were loaded into each pail. Generally, 100 to 120 pails were filled each day (approximately 1,500 pounds of soil).

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Originally, excavation of soils was to take place on a daily basis to avoid the excessive loss of VOC's from the soils. However, based upon monitoring of the head space in selected pails, it was obvious that minimal VOC losses occurred if the soil was stored for more than one day. On those occasions where sufficient soil was excavated for two test runs, the excavation did not occur on the following day of processing. The process runs that utilized soils from the previous day's excavation were Runs 12, 17, 20, 23, 25, and 26.

A composite sample was taken of all soils immediately prior to being fed to the unit. Therefore, even if minimal VOC losses occurred from overnight storage, the appropriate concentration would be reflected in the feed soil sample.

7.2.1.2 Soil preparation. As previously mentioned, sufficient soil for at least one full day of operation was excavated and stored in sealed, five-gallon capacity metal containers. The soil containers were sampled, sealed, and manually loaded into the bucket of a backhoe for transportation to the processing area. The backhoe was required to travel only a short distance (i.e., approximately 300 feet north and 260 feet west), as shown on Figure 3-2. The truck route was confined to the installation boundaries. At the time of processing, the pails were opened, sampled, and fed to the unit.

7.2.1.3 Processed soil handling. At the beginning of each test run, an empty 55-gallon drum was placed below the soil discharge gate. Only those soils that represented treatment under stable test conditions were collected for sampling. At the end of the test run, or when the drum was full, the processed soil drum was removed and the composite soil samples were deposited in a separate pail. The sample pail was stored on ice in an insulated cooler until the processed soil was split into the appropriate sample bottles.

7.2.1.4 Air flow rate. Originally, the air flow rate was to remain fixed at 200 cubic feet per minute (cfm). However, preliminary field tests raised concerns over the amount of dust and particulate that would be generated by an air flow rate of 200 cfm. As no precautions were being taken to prohibit particulate from discharging to the atmosphere, the air flow rate was decreased to 100 cfm. (Test Runs 27 and 28 evaluated reprocessing soils that had already been treated but still contained a contaminant residue. Since the treated soils were relatively dry, the potential for excessive dust generation existed. Therefore, the air flow rate was decreased to 75 cfm during these test runs).

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7.2.2 Control test variables held constant at various levels. In order to evaluate the economic feasibility of using a thermal processor for low temperature thermal stripping of soils contaminated with volatile organic compounds, three variables emerged as key factors. These variables consisted of the soil discharge temperature, soil residence time, and air inlet temperature. The test runs included various levels for each of these test variables, as discussed in the following subsections.

7.2.2.1 Soil discharge temperature/heating oil conditions. The thermal processor was an indirect heat exchanger. As such, the heating medium never actually contacted the soil medium. Rather, heat exchange was by conduction through the flights, shafts, and trough of the processor. The only means of controlling the temperature of soil, therefore, was to control the temperature of the oil. The circulating oil could be heated from ambient up to a maximum temperature of 315°C (600°F). Phase I test runs evaluated three soil discharge temperatures: 50°C (122°F), 100°C (212°F), and 150°C (302°F). Phase II test runs also included evaluation of the maximum attainable soil discharge temperature.

7.2.2.2 Soil residence time. The test plan indicated that three soil residence times would be maintained during various runs in Phase I of the pilot study. The three soil residence times were originally 20 minutes, 40 minutes, and 60 minutes. However, field tests indicated that a minimum residence time of 30 minutes was required to achieve the desired soil discharge temperature of 150°C. Therefore, the soil residence times evaluated during the Phase I base case test runs were changed to 30 minutes, 45 minutes, and 60 minutes. Extended soil residence times of 75 and 90 minutes were evaluated during Phase II of the pilot investigation. These values were selected based on the minimum rotational speed of the screws, i.e., maximum residence time. The slowest screw speed corresponded to approximately 90 minutes residence time. The 75 minute residence time was chosen as a mid-point value.

7.2.2.3 Air temperature at inlet. Two inlet air temperatures were evaluated during the pilot investigation: ambient air temperature and approximately 90°C (200°F). The elevated temperature was maintained using an electrical resistance heater.

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7.2.2.4 Soil feed rate. The processor was fed sufficient soil to maintain a constant level in the trough (i.e., 2/3 full). This constant volume corresponded to the following mass feed rates: 300 #/hr, 225 #/hr, 150 #/hr, 125 #/hr, and 100 #/hr for 30 minute, 45 minute, 60 minute, 75 minute, and 90 minute residence times, respectively.

7.3 Response variables measured. The response variables measured during the pilot investigation were the soil discharge composition/conditions and the air discharge composition/conditions.

7.3.1 Processed soil composition/conditions.

7.3.1.1 VOC concentrations. The volatile organic compound concentrations varied at all points throughout the thermal processor. However, interest pertained primarily to the processed soil. Therefore, composite samples of the discharge soil were collected and analyzed for volatile organic compounds.

7.3.1.2 Moisture content. Treatment in the thermal processor reduced the moisture content of the soils. To determine the amount of moisture that evaporated, the processed soils were sampled and analyzed for moisture content.

7.3.1.3 Mass flow rate. The volatile organic compounds and moisture evaporated in the processor; therefore, the mass of soil entering the unit was not the same as the mass of soil discharging the unit. To determine the approximate mass of compounds removed as a vapor, the soil leaving the unit was weighed.

7.3.2 Air discharge composition/conditions. The off-gas manifolds were monitored and sampled for VOC concentrations, moisture content, and temperature.

7.3.2.1 VOC concentrations. During Phase I test runs, the three exhaust air manifolds were monitored separately to detect the concentration of total VOC's. A portable field instrument was used to monitor the gross VOC concentrations. In addition, the common header was continuously sampled using a modified Volatile Organic Sampling Train (VOST) for analysis by the WESTON Laboratory. The continuous sample was analyzed using GC/MS techniques to identify and quantify VOC's in the air stream. During Phase II test runs, VOCs were monitored using a portable field instrument at the afterburner inlet (Test Runs 19 through 23) and manifold 2 (Test Runs 25 through 28). Modified VOST was also used at each leg of the off-gas manifold (Test Runs 19 through 23).

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7.3.2.2 Moisture content. The moisture in the soil evaporated in the thermal processor, exiting as vapor in the air discharge stream. To determine the amount of moisture that existed in the unit, the moisture content of the air stream was routinely monitored.

7.3.2.3 Temperature. The temperature of the air stream changed as it travelled through the processor. Therefore, the air temperature was monitored at the air heater outlet at each exhaust port as well as at the common header port.

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8. SAMPLING TECHNIQUES AND ANALYTICAL METHODS

A brief discussion of the techniques used to sample the soil and air streams, as well as the laboratory methods used to analyze the samples, is contained in the following subsections. An instrumentation diagram showing the location of measuring devices is included in Figure 8-1.

8.1 Field sampling techniques.

8.1.1 Soil sampling techniques. A list of the soil parameters that were monitored and/or sampled for analysis is contained in Table 8-1. As shown, five parameters were monitored or sampled for in the field: temperature, mass feed rate, density, moisture content, and those VOC's on the Hazardous Substance List (Appendix A).

8.1.1.1 Temperature. The temperatures of the feed and processed soils were monitored using a chromel/alumel thermo- couple and sampling device fabricated specifically for that purpose. An illustration of the sampling device is shown in Figure 8-2.

An open-top carbon steel sample container was used to hold the soils being monitored. Approximate dimensions of the sample cup were 3 inches long by 3 inches wide by 2 inches high. A carbon steel handle was welded to the side of the box to facilitate soil collection. A small hole was drilled into the side of the sample box, just above the handle, for insertion of the thermocouple. The thermocouple was wired to a multi-point calibrated digital pyrometer for accurate reading of temperature.

The temperature of the feed and processed soils were monitored and recorded every 30 minutes. When monitoring the temperature of the feed soil, the sampling device was fully submerged into a pail of feed soil. The thermocouple was allowed to stabilize and the associated temperature was recorded. When monitoring the temperature of the processed soils, the sample cup was placed directly under the discharge soil gate. To allow the container to come to an equilibrium temperature with the soil, the sample container was filled with soil exiting the unit, and the contents were dumped into the processed soil drum. The cup was refilled, sufficient time elapsed for the thermocouple to stabilize, and the temperature was recorded. For quality control purposes, the entire procedure was repeated.

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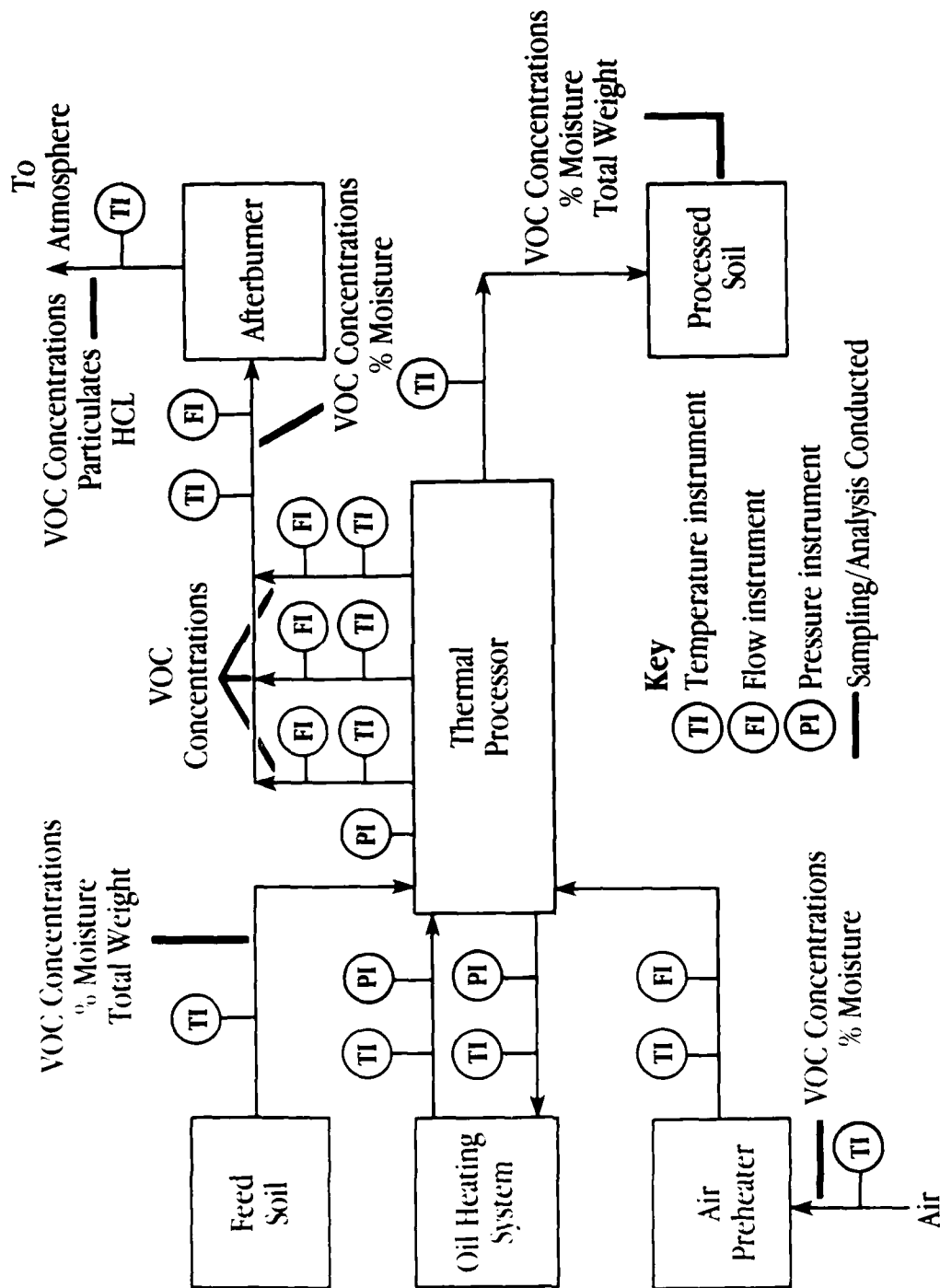
FIGURE 8-1   THERMAL PROCESSING SYSTEM INSTRUMENTATION
AND SAMPLING/ANALYSIS DIAGRAM

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TABLE 8-1.   PARAMETERS MONITORED AND/OR SAMPLED FOR IN SOILS

1.	Temperature	–	Feed Soil Processed Soil
2.	Mass Feed Rate of Soil	–	Feed Soil Processed Soil
3.	Density	–	Feed Soil Processed Soil
4.	Moisture Content	–	Excavated Soil Feed Soil Processed Soil
5.	VOC's	–	Excavated Soil Feed Soil Processed Soil

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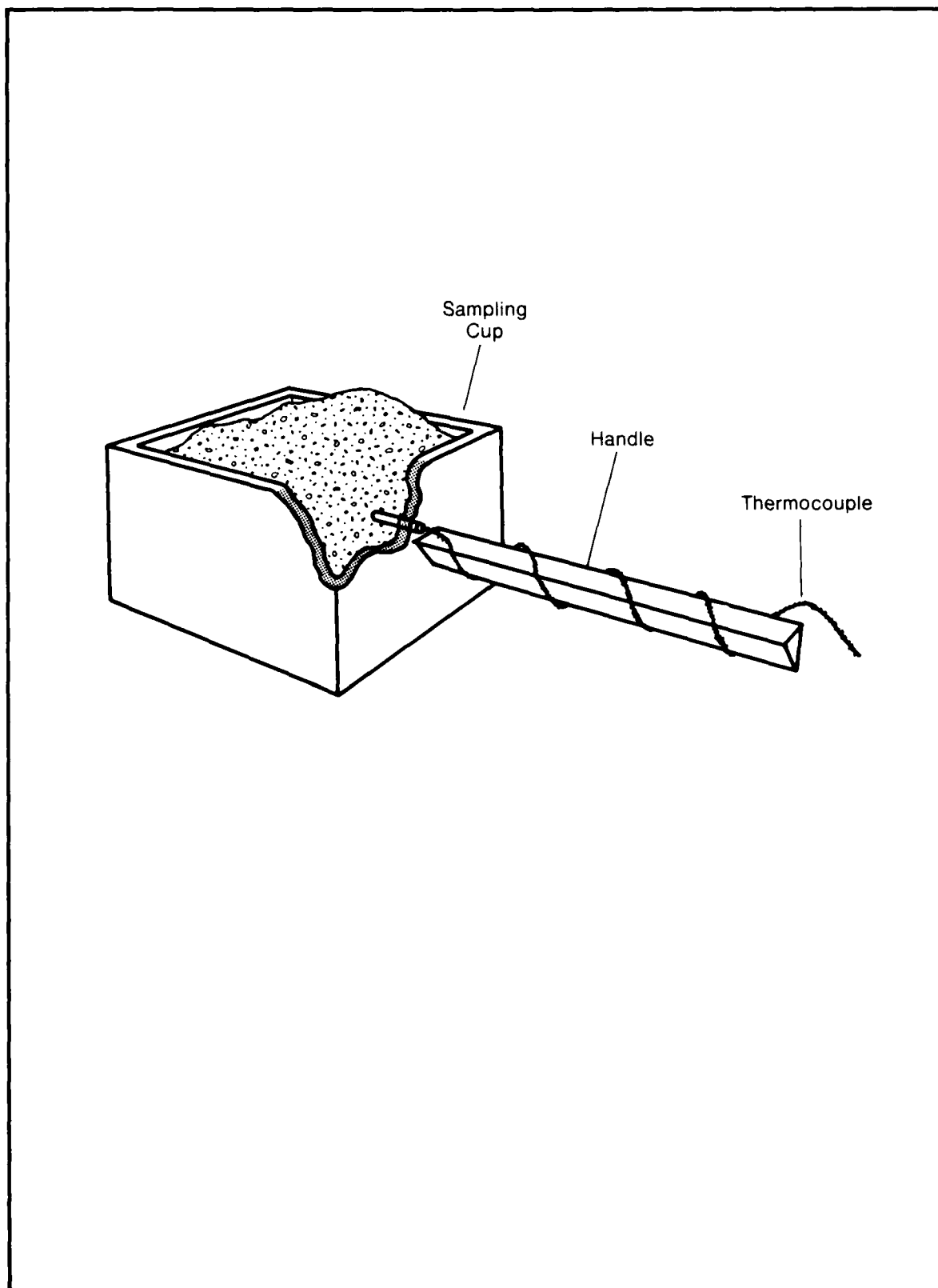
FIGURE 8-2   SAMPLING DEVICE USED TO MONITOR SOIL TEMPERATURE

8.1.1.2 Mass feed rate of soil. The weight of each pail of feed soil was recorded prior to being loaded into the thermal processor. The mass feed rate of soil was determined using the total weight of soil divided by the duration (in hours) of the test run. The weight of the processed soils was also recorded to determine the mass feed rate of the processed soil.

8.1.1.3 Density. The weight and volume of soils, both feed and processed, were monitored and recorded to determine the associated soil density.

8.1.1.4 Moisture content. A 40-milliliter VOA vial was filled for each type of soil (i.e., excavated, feed, and processed), for determination of the moisture content. The vials were stored on-site until delivery to the WESTON Laboratory for analysis.

8.1.1.5 VOC's. A 40-milliliter VOA vial was filled with a composite soil sample of the excavated, feed, and processed soils to be analyzed for those VOC's on the Hazardous Substance List. Sample collection was conducted at the end of each test run. The soil samples were stored on ice until delivery to the WESTON laboratory.

8.1.2 Air sampling techniques. A list of the test locations for each test run, as well as the parameters for which samples were collected is shown in Table 8-2. A detailed discussion of the air sampling techniques is contained in Appendix C. A brief discussion follows.

8.1.2.1 Testing locations. Sample test ports were installed at the following four locations: (1) process air inlet, (2) each leg of the off-gas manifold, (3) the afterburner inlet, and (4) the afterburner stack. The test port locations were in compliance with EPA Method 1'.

8.1.2.2 Testing equipment and methodology. Following equipment set-up, the air sampling technicians compiled preliminary test data at all source locations. Geometric flue measurements were recorded and pitot tube traverses were performed to determine the presence/absence of cyclonic flow.

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TABLE 8-2.   AIR SAMPLING PARAMETERS MEASURED IN THE FIELD
             FOR EACH TEST LOCATION

Test run	Parameter	Location			
		Process air inlet	Off-gas manifold	After-burner inlet	After-burner stack

Phase I - Base case test runs

Test run	Parameter	Process air inlet	Off-gas manifold	Afterburner inlet	Afterburner stack
1-7	Flow	X	X	X	
	Temperature	X	X	X	
	Moisture	X		X	
	Total VOC's	X	X		
	Specific VOC's			X	
	Fixed Gases*	X	X	X	
	Particulate				
	Hydrochloric Acid				
8-10	Flow	X	X	X	X
	Temperature	X	X	X	X
	Moisture	X		X	X
	Total VOC's	X	X		
	Specific VOC's			X	X
	Fixed Gases*	X	X	X	X
	Particulate				X
	Hydrochloric Acid				X
11-18	Flow	X	X	X	X
	Temperature	X	X	X	X
	Moisture	X	X		
	Total VOC's	X	X		
	Specific VOC's			X	
	Fixed Gases*	X	X	X	
	Particulate				
	Hydrochloric Acid				

*Fixed gases are CO_2, O_2, and CO.
**No continuous emissions monitoring (CEM) due to faulty
  instrument.

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TABLE 8-2. (CONTINUED)

Test run	Parameter	LOCATION			
		Process air inlet	Off-gas manifold	After-burner inlet	After-burner stack

Phase II - Optimization Test Runs

Test run	Parameter	Process air inlet	Off-gas manifold	After-burner inlet	After-burner stack
19-23	Flow	X	X	X	X
	Temperature	X	X	X	X
	Moisture	X		X	
	Total VOC's	X		X	
	Specific VOC's		X		
	Fixed Gases*	X	X	X	
	Particulate				
	Hydrochloric Acid				
24	Flow	X	X	X	X
	Temperature	X	X	X	X
	Moisture	X		X	
	Total VOC's**				
	Specific VOC's				
	Fixed Gases*	X	X	X	
	Particulate				
	Hydrochloric Acid				
25-28	Flow	X	X	X	X
	Temperature	X	X	X	X
	Moisture	X		X	
	Total VOC's		X		
	Specific VOC's				
	Fixed Gases*	X	X	X	
	Particulate				
	Hydrochloric Acid				

*Fixed gases are CO_2, O_2, and CO.
**No continuous emissions monitoring (CEM) due to faulty instrument.

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Simultaneous testing was performed at the process air inlet, each leg of the off-gas manifold, and the afterburner inlet during the first 23 test runs. In addition, concurrent compliance tests were performed at the afterburner discharge stack during a selected low, medium, and high VOC-inlet loading condition (i.e., Test Runs 8, 9 and 10, respectively). Testing protocols followed for each parameter measured are summarized in Table 8-3.

8.1.2.2.1 Flow. Standard pitot tubes were used in conjunction with inclined manometers to measure the flow at the process air inlet and afterburner inlet. Air flow in the legs of the off-gas manifold was measured via orifice plates; magnahelics were used to measure the associated orifice plate pressure differentials. Air flow at the afterburner discharge stack was determined using a modified EPA Method 5 Train.[5]

8.1.2.2.2 Temperature. The temperatures of the appropriate air streams were monitored using chromel/alumel thermocouples placed alongside the pitot tubes or orifice plates. The thermocouples were wired to a multi-point calibrated pyrometer for accurate digital readout.

8.1.2.2.3 Moisture content. The process air and infiltration air were assumed to be the same as ambient air. The moisture content of the ambient air was measured using a sling psychrometer and associated psychrometric chart. The moisture content at the afterburner inlet was measured using an EPA Method 4 sampling train.[5] The moisture content at the discharge stack was determined using a modified EPA Method 5 sampling train.[5]

8.1.2.2.4 VOC's.

8.1.2.2.4.1 VOC's in off-gas manifold system. Three sampling techniques were used to monitor the VOC concentration in the air discharge stream: 1) continuous emissions monitoring (CEM) system; 2) mobile mass spectrometer; and 3) modified VOST. A brief description of sampling techniques is contained in the following subsections.

8.1.2.2.4.1.1 Total VOC's by continuous emissions monitoring (CEM) system. Total VOC concentrations in air were measured at the processor inlet during each test run; at each leg of the off-gas manifold for Test Runs 1 through 18; at the afterburner inlet for Test Runs 19 through 23; and at manifold

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TABLE 8-3.   TESTING PROTOCOLS FOR AIR SAMPLING

Parameters measured	EPA reference methods[?]
Air Temperature, Volumetric Flow, and Mass Rate	EPA 1, 2 (modified by using centerpoint velocities)
Fixed Gases (CO_2, O_2, and CO) Concentration	EPA 3 (stack only)
Moisture Concentration	EPA 4 (sling psychrometer at process inlet)
Volatile Organic Compounds Concentration	
Total VOC by CEM	EPA 25A (modified by using PID monitor for runs 1-11)
Specific VOC by Modified VOST	WESTON designed
Specific VOC by VOST	EPA 600/8-84-007, March 1984
Particulate and Hydrogen Chloride Concentration and Mass Rate	EPA 5 (modified by replacing impinger solutions with 0.1 N NaOH analyzed for hydrochloric acid by standard methods)

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2 for Test Runs 25 through 28. The CEM system measured gross VOC concentrations in the linear range from 1 to 600 ppm (by volume, dry basis) relative to the calibration gas (benzene). Benzene was chosen as the calibration gas instead of one of the major contaminants (i.e., dichloroethylene or trichloroethylene). This selection was based on the following rationale:

(a) One of the major uses of portable VOC detectors is during site assessment (i.e., identification and quantification of contaminants). On these occasions, the major contaminants are unknown; therefore, it is not possible to pre-calibrate the instrument with a contaminant of concern. A common calibration gas that is readily available (such as benzene) would be used on these sites.

(b) Benzene, a common calibration gas, is stored as a stock item by suppliers. Specialty gases such as dichloroethylene or trichloroethylene, however, are made to order and, as such, typically require one month leadtime.

(c) Specialty gases such as dichloroethylene or trichloroethylene are more expensive than readily available gases such as benzene (typical costs: cylinder of 10 ppm dichloroethylene in air - $280; cylinder of 10 ppm benzene in air - $128).

(d) The stability of specialty gases such as dichloroethylene or trichloroethylene in air are questionable. The supplier suspects that the concentration of dichloroethylene or trichloroethylene would decrease over time.

Gross VOC concentrations were measured using an AID Model 590 volatile organics monitor/GC (photoionization detector with 10.0 eV lamp) for Test Runs 1 through 11, and a Century Model 128 volatile organics monitor/GC (Flame ionization detector) for Test Runs 12 through 23 and 25 through 28. The total VOC concentrations were not monitored during Test Run 24 due to a faulty instrument. The total VOC concentrations were recorded using a Molytek single channel recorder.

8.1.2.2.4.1.2 Total VOC's by mobile mass spectrometer. A Bruker MM1 mobile mass spectrometer was on-site on 6, 8, and 9 August 1985. The MM1 was used to qualitatively identify VOC's in the dischrge air stream. Authentic standard compounds were used to mass calibrate the MM1. Manifolds 1, 2, and 3 were sampled with the MM1 during Test Runs 2, 4, and 5. The instrument probe was placed approximately 2 inches from the sampling port. Each sampling interval was approximately 30 seconds. Multiple runs were made at each sampling port during a 10-minute interval. The MM1 instrument recorded and printed a complete mass spectrum from each sampling event. The spectra were examined and analyte identifications were confirmed.

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8.1.2.2.4.1.3 Specific VOC's by modified VOST. Specific VOC concentrations were measured at the afterburner inlet for Test Runs 1 through 18 and at each leg of the off-gas manifold for Test Runs 19 through 23 using a modified VOST.[ ] Modification was required since the VOC concentrations at these locations were too high to be accommodated by a standard VOST (i.e., greater than 500 ppm by volume). The major modification included an increased mass of activated charcoal to fully absorb the VOC's. A detailed description of the modified VOST is included in Appendix C.

8.1.2.2.4.2 VOC's in stack discharge. Specific VOC concentrations were measured at the discharge stack during Test Runs 8, 9, and 10 using a standard VOST.[ ] This sampling train was applicable to the lower concentrations (i.e., less than 500 ppm by volume) encountered at this location.

8.1.2.2.5 Particulate and hydrochloric acid. Particulate and hydrochloric acid (HCl) in the discharge stack gases were collected simultaneously using a modified EPA Method 5 sampling train[ ] during Test Runs 8, 9, and 10.

8.1.2.2.6 Fixed gases (carbon dioxide, oxygen, and carbon monoxide). Fixed gases were monitored for all test runs in the discharge stack gases using an EPA Method 3 sampling train.[ ]

8.2 **Analytical techniques.** All soil, air, and water (condensate from the off-gases) samples were stored on ice until delivery to the WESTON Laboratory. Upon arrival at the laboratory, all chain-of-custody forms were signed and samples were recorded in a bound log book. All sample containers were maintained at 4°C until analysis. No samples were retained longer than allowable holding times (i.e., 14 days). The analytical parameters and methods are listed in Table 8-4. A copy of the analytical methods is contained in Appendix E. A brief discussion follows.

8.2.1 VOC's.

8.2.1.1 VOC's in soil. Volatile organics in soil samples were analyzed using the EPA Contract Laboratory Protocol (CLP) method for "GC/MS Analysis of Purgeable Organics in Soils and Sediments." Low level samples (i.e. those containing 5 to 2000 ppb) were by the "low level protocol" in which an inert gas was bubbled through a mixture of a 0.005 to 5 gram sample and reagent water contained in a purging chamber at elevated temperatures. The purgeables were efficiently transferred from

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TABLE 8-4. ANALYTICAL PARAMETERS AND METHODOLOGIES

Parameter	Method
A. VOC's in soil.	EPA Contract Laboratory Protocol (CLP) for GC/MS Analysis of Purgeable Organics in Soils and Sediments.
B. VOC's in the Air Stream.	
1. VOST Tubes	EPA Protocol for the Analysis of Volatile Principle Organic Hazardous Constituents (POHC's) using VOST in conjunction with the National Institute for Occupational Safety and Health (NIOSH) Method No. P&CAM 127 and the EPA CLP Method for GC/MS Analysis of Purgeable Organics.
2. Condensate	EPA CLP Method for GC/MS Analysis of Purgeable Organics.
C. Moisture Content of Soil.	Standard Method 209G.

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the aqueous phase to the vapor phase. The vapor was swept through a sorbent column where the purgeables were trapped. After purging was completed, the sorbent column was heated and backflushed with the inert gas to desorb the purgeables onto a gas chromatographic column. The gas chromatograph was temperature programmed to separate the purgeables which were then detected with a mass spectrometer.

Samples containing higher levels (i.e. greater than 2000 parts per billion) of purgeable organics were analyzed using the "medium level protocol." In this procedure a measured amount of soil was extracted with methanol. A portion (5 to 100 milliliters) of the methanol extract was diluted to 5 milliliters with reagent water. An inert gas was bubbled through this solution in a specifically designed purging chamber at ambient temperature. The purgeables were effectively transferred from the aqueous phase to the vapor phase. The vapor was swept through a sorbent column where the purgeables were trapped. After purging was completed, the sorbent column was heated and backflushed with the inert gas to desorb the purgeables onto a gas chromatographic column. The gas chromatograph was temperature programmed to separate the purgeables which were then detected with a mass spectrometer as described in the CLP methods for "GC/MS Analysis of Purgeable Organics in Soils and Sediments," provided in Appendix E.

8.2.1.2   VOC's in air.

8.2.1.2.1   VOST tubes. Volatile organics collected on Tenax/Tenax charcoal (VOST tubes) were analyzed by the procedure described in the VOST protocol in which VOST cartridges were thermally desorbed onto an analytical Tenax Trap, which was subsequently desorbed onto a GC/MS system and analyzed by procedures given in the EPA CLP method for "GC/MS Analysis of Purgeable Organics." Charcoal tube samples were desorbed with carbon disulfide (NIOSH Method No. P&CAM 127). The carbon disulfide extracts were analyzed by direct injection using GC/MS procedures given in the CLP method for "GC/MS Analysis of Purgeable Organics."

8.2.1.2.2   Condensate. Volatile organics in water samples were analyzed using the EPA CLP method for "GC/MS Analysis of Purgeable Organics." In this method an inert gas was bubbled through a 5-milliliter sample contained in a specifically designed purging chamber at ambient temperature. The purgeables

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were efficiently transferred from the aqueous phase to the vapor phase. The vapor was swept through a sorbent column where the purgeables were trapped. After purging was completed, the sorbent column was heated and backflushed with the inert gas to desorb the purgeables onto a gas chromatographic column. The gas chromatograph was temperature programmed to separate the purgeables which were then detected with a mass spectrometer. An aliquot of the sample was diluted with reagent water when dilution was necessary. A 5-milliliter aliquot of the dilution was taken for purging.

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9. PRESENTATION OF DATA

Detailed field and analytical data associated with the Phase I
and Phase II test runs are included in Appendix F. Pertinent
data is also summarized, in a mass/energy balance format, in
Appendix G. For convenience, Table 9-1 summarizes the range of
each test variable as well as the average value. A brief
discussion of the independent, controlled, and response
variables is contained in the following subsections.

9.1 Independent variables.

9.1.1. Actual feed soil composition/conditions.

9.1.1.1. VOC concentrations. The excavated and feed soils
were sampled to estimate the amount of VOC's that were lost to
fugitive emissions. Table 9-2 summarizes the VOC concentrations
that were determined to be present in the excavated and feed
soils. These VOC concentrations were determined by using
laboratory GC/MS analytical techniques.

With the exception of the feed soils corresponding to Test
Runs 24 through 28, the VOC concentrations listed on Table 9-2
were not used in any other portion of the evaluation (i.e., VOC
removal efficiencies, mass/energy balances, or statistical
interpretation). Rather, the VOC concentrations in the feed
soil were "backed out" using the VOC concentrations in both the
processed soils and air discharge stream, as well as the
following equation:

$$IN \quad = \quad OUT$$

VOC's in Feed Soil = VOC's in Processed Soil + VOC's in
Discharge Air

The decision to use the "backed out" feed concentration was
based on the following logic:

1. Although every effort was made to sample the process
    streams in a fashion that would enable derivation of a
    mass balance, this is not a realistic expectation,
    especially when dealing with a nonhomogeneous soil
    medium. In order to develop a mass balance, one of the
    streams must be allowed to "float," its value being
    derived from the remaining streams. The system was
    reviewed to determine which stream should be
    designated for derivation.

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TABLE 9-1. SUMMARY OF VALUES OF TEST VARIABLES FOR PHASE I AND PHASE II OF THE PILOT STUDY

	Phase I		Phase II	
	Range	Average	Range	Average
A. INDEPENDENT VARIABLES				
1. Feed Soil Composition/Conditions				
a. VOC Concentrations (ppm by weight)				
1) 1,2-trans Dichloroethylene	0 - 940	374	0 - 35	10
2) Trichloroethylene	0.05 - 3,476	1,638	0.01 - 2,300	410
3) Tetrachloroethylene	0.08 - 2,907	698	0 - 890	196
4) Xylene	0.03 - 27,197	1,594	11 - 58	35
5) Other VOC's	0 - 145	30	0 - 33	14
6) Total VOC's	7 - 31,923	4,333	24 - 3,324	664
b. Moisture Content (percent by weight)	13.80 - 26.40	19.30	15.0 - 20.60	17.30
c. Temperature (°C)	20.20 - 30.97	25.46	14.2 - 31.1	22.6
2. Air Inlet Composition/Conditions				
a. VOC Concentrations				
1) Total VOC's (ppm by volume)	<1.0 - <1.0	<1.0	<1.0 - <1.0	<1.0
b. Moisture Content (percent by weight)	1.5 - 3.0	2.1	0.8 - 2.4	1.6
c. Ambient Temperature (°C)	23.0 - 33.0	27.2	17.0 - 33.0	25.0
B. CONTROL VARIABLES				
1. Held Constant At All Levels				
a. Air Flow Rate (lbs/hour)				
1) Process Air	102 - 234	173	138 - 197	168
2) Infiltration Air	145 - 270	203	176 - 286	235
2. Held Constant At Various Levels				
a. Soil Discharge Temperature (°C)				
1) Level 1	49.7 - 66.3	56.4	59.8 - 62.8	60.9
2) Level 2	95.4 - 120.9	103.5	141.0 - 150.0	145.5
3) Level 3	137.3 - 175.3	155.0	174.6 - 232.7	206.8

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TABLE 9-1. (CONTINUED)

	Phase I		Phase II	
	Range	Average	Range	Average
A. b. Soil Residence Time (minutes)				
1) Level 1	28.9 - 30.2	29.6	58.0 - 60.2	58.8
2) Level 2	43.7 - 46.4	44.8	N/A	75.7
3) Level 3	58.3 - 61.2	59.4	85.6 - 88.5	86.7
c. Air Temperature at Inlet (°C)				
1) Level 1 (target - ambient)	23 - 29	26	17 - 21	20
2) Level 2 (target - 90°C)	61 - 99	86	96 - 98	97
C. RESPONSE VARIABLES MEASURED				
1. Processed Soil Composition/Conditions				
a. VOC Concentrations (ppm by weight)				
1) 1,2-trans Dichloroethylene	0 - 160	10	0 - 13	2
2) Trichloroethyle	0 - 880	59	0.01 - 52	8
3) Tetrachloroethylene	0 - 400	45	0 - 48	6
4) Xylene	0 - 64	6	0 - 6	1
5) Other VOC's	0 - 13	1	0.10 - 3	1
6) Total VOC's	0.01 - 1,517	122	0.30 - 112	17
b. Moisture Content (percent by weight)*	0.1 - 13.8	4.4	0.1 - 4.5	1.8
c. Mass Flow Rate (lbs/hr - wet feed basis)	142 - 383	216	109 - 232	164
2. Air Discharge Composition/Conditions				
a. VOC Concentrations (ppm/vol)				
1) 1,2-trans Dichloroethylene	0 - 208	66	0 - 0.5	0.20
2) Trichloroethylene	0 - 785	215	0 - 0.2	0.06
3) Tetrachloroethylene	0 - 237	58	0 - 0	0
4) Xylene	0 - 3,184	192	1.4 - 5.0	2.80
5) Other VOC's	0 - 33	6	1.2 - 3.0	2.30
6) Total VOC's	1.1 - 3,624	537	3.7 - 8.0	5.30
b. Moisture Content (percent by weight)	4.8 - 22.7	12.6	5.4 - 14.8	9.60
c. Temperature (°C)	34 - 118	71	44 - 117	81

N/A: Not applicable - only 1 test run evaluated 75 minute residence time.
* Does not include moisture content of treated soil reprocessed during test runs 27 and 28 (i.e., 1.0 and 0.1 percent, respectively).

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TABLE 9-2. COMPARISON OF VOC CONCENTRATIONS IN EXCAVATED SOILS AND FEED SOILS (PPM BY WEIGHT)

Run test	Dichloroethylene Excavated	Feed	Trichloroethylene Excavated	Feed	Tetrachloroethylene Excavated	Feed	Xylene Excavated	Feed	Other VOC's Excavated	Feed	Total VOC's Excavated	Feed
I. Phase I Test Runs												
1	0.48	0.55	0.64	0.21*	0.13*	0.03*	0.12*	BDL	0.03*	0.76	1.40	1.55
2	110.00	63.00	3,600.00	1,600.00	4,800.00	1,500.00	35.00*	18.00	10.40*	6.20*	8,555.40	3,187.20
3	3.10	0.08*	1.50	1.40	4.70	3.90	0.26	0.07*	0.06*	0.02*	9.62	5.46
4	0.21	0.03*	0.29	0.04*	0.81	0.18	BDL	BDL	0.04*	BDL	1.35	0.25
5	830.00	330.00	20,000.00	19,000.00	580.00	950.00	460.00	320.00	117.00*	70.00*	21,987.00	20,670.00
6	770.00	210.00	8,400.00	11,000.00	39.00*	70.00*	240.00	380.00	56.00*	88.00*	9,505.00	11,748.00
7	1.20	0.30*	1.50	0.63*	0.84*	0.41*	BDL	BDL	0.62*	BDL	4.16	1.34
8	110.00	220.00	1,200.00	5,900.00	190.00	930.00	97.00*	240.00	12.05*	50.00*	1,609.05	7,340.00
9	1,200.00	470.00	2,640.00	930.00	BDL	98.00*	47.00*	20.00*	269.60	BDL	4,156.60	1,518.00
10	270.00	140.00	2,200.00	1,300.00	1,300.00	1,500.00	110.00	120.00	26.60*	22.00*	3,906.60	3,082.00
11	100.00	73.00	830.00	760.00	530.00	410.00	60.00	49.00*	17.30*	7.10*	1,537.30	1,299.10
12					NO EXCAVATION							
13	62.00	47.00	39.00*	55.00	30.00*	61.00	29.00*	23.00	BDL	5.42*	160.00	191.42
14	150.00	80.00	1,600.00	28.00*	230.00	61.00	150.00	59.00	28.30*	10.00*	2,138.30	238.00
15	310.00	320.00	2,200.00	1,800.00	2,300.00	2,500.00	140.00	180.00	35.00*	13.20*	4,985.00	4,813.20
16	140.00	210.00	950.00	150.00	1,900.00	1,500.00	13.00*	73.00	40.80	50.00*	3,043.80	1,983.00
17					NO EXCAVATION							
18	BDL	2.40*	BDL	1.00*	8.00*	3.30*	BDL	BDL	BDL	BDL	8.00	6.70
Average	252.30	155.40	2,728.90	2,657.90	744.60	599.20	86.30	92.60	38.40	20.20	3,850.60	3,503.30

*Estimated value
BDL - Below Detection limit

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TABLE 9-2. (CONTINUED)

II. Phase II Test Runs

Test run number	Dichloroethylene Excavated	Feed	Trichloroethylene Excavated	Feed	Tetrachloroethylene Excavated	Feed	Xylene Excavated	Feed	Other VOC's Excavated	Feed	Total VOC's Excavated	Feed
19	1.80*	0.75*	BDL	BDL	BDL	BDL	6.30	3.30	1.50*	0.53*	9.60	4.58
20					NO EXCAVATION							
21	0.02*	0.02*	0.08*	0.07*	0.03*	0.03*	0.10	0.16	BDL	0.02*	0.22	0.30
22	0.45*	BDL	BDL	BDL	BDL	BDL	79.00	34.00	34.76	5.60	114.21	39.60
23					NO EXCAVATION							
24	74.00	22.00	>390.00	180.00	>260.00	140.00	>7,190.00	18.00	16.80	5.52	>930.80	365.52
25					NO EXCAVATION							
26					NO EXCAVATION							
27	13.00*	BDL	340.00	83.00	210.00	120.00	35.00*	23.00	BDL	BDL	598.00	226.00
28					NO EXCAVATION							
Total	89.27	22.77	>730.08	263.07	>470.03	260.03	>310.40	78.46	53.06	11.67	>1,652.83	636.00

*Estimated Value
BDL – Below Detection Limit

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2. Upon consideration of the three process streams i.e., feed soil, processed soil, and discharge air, the highest level of confidence was placed in the samples recovered from the discharge air stream. First, the air stream was far more homogeneous than the soil streams. Second, the air stream was monitored <u>continuously</u> over the entire duration of the test. The air sample was passed through a highly efficient VOST train that effectively removed the VOC's. Therefore, the air stream composite sample was assumed to be the most representative. The next decision was which of the two remaining streams was the more representative.

3. Due to the extremely nonhomogeneous nature of the soil, it is highly unlikely that the one gram sample (approximately) of feed soil that was analyzed using GC/MS techniques was representative of the soils that were actually fed to the unit over the entire duration of the test. Admittedly, this is also true of the processed soils; however, the level of confidence associated with the processed soil sample is higher than that of the feed soil. The feed soil was generally full of clumps, moist, and irregular in consistency. In addition, the concentrations of VOC's in the feed soil were normally very high; therefore, the potential for masking of the lower concentration compounds by the higher concentration compounds existed, since the detection limits were high. The processed soil, on the other hand, was thoroughly mixed inside the processor. The flights of the screws meshed with each other to effectively break down the lumps that were inherent in the feed soil. In addition, the processed soils were dry, more regular in consistency, and the concentrations of VOC's were much lower than those of the feed soil. With these considerations, the composite processed soil sample was assumed to be the more representative. The feed soil concentrations were backed out using the processed soil and air discharge streams.

During Test Runs 24 through 28, the air discharge stream was not monitored. Therefore, for these test runs the only alternative was to assume that the laboratory GC/MS analyses for VOC's in the feed soil was representative. For comparison purposes, Table 9-3 summarizes the values corresponding to the feed soil laboratory determined via GC/MS analytical results and the values corresponding to the "backed out" feed soil concentrations.

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TABLE 9-5. COMPARISON OF LABORATORY GC/MS ANALYTICAL RESULTS AND DERIVED CONCENTRATIONS IN THE FEED SOIL (PPM BY WEIGHT)

Run test	Dichloroethylene Laboratory	Dichloroethylene Derived	Trichloroethylene Laboratory	Trichloroethylene Derived	Tetrachloroethylene Laboratory	Tetrachloroethylene Derived	Xylene Laboratory	Xylene Derived	Other VOC's Laboratory	Other VOC's Derived	Total VOC's Laboratory	Total VOC's Derived
I. Phase I Test Runs												
1	0.55	BDL	0.21*	BDL	0.03*	BDL	BDL	BDL	0.76	BDL	1.55	BDL
2	63.00	560.70	1,600.00	3,306.35	1,500.00	2,907.05	18.00	23.48	6.20*	10.09	3,187.20	6,807.68
3	0.08*	BDL	1.40	24.24	3.90	54.55	0.07*	36.34	0.02*	BDL	5.46	115.14
4	0.03*	BDL	0.041*	0.05	0.18	6.47	BDL	0.029	BDL	0.06	0.25	6.60
5	330.00	939.86	19,000.00	3,475.60	950.00	596.45	320.00	298.22	70.00*	144.59	20,670.00	5,454.72
6	210.00	529.40	11,000.00	2,907.30	70.00*	50.50	380.00	291.58	88.00*	89.69	11,748.00	3,868.47
7	0.30*	0.17	0.63*	30.40	0.41*	0.08	BDL	7.54	BDL	BDL	1.34	38.19
8	220.00	290.84	5,900.00	1,955.26	930.00	699.13	240.00	85.97	50.00*	12.50	7,340.00	3,043.70
9	470.00	889.06	930.00	1,997.44	98.00*	346.21	20.00*	106.90	BDL	38.92	1,518.00	3,378.54
10	140.00	586.11	1,300.00	2,678.54	1,500.00	1,422.03	120.00	27,197.37	22.00*	39.13	3,082.00	31,923.17
11	73.00	264.04	760.00	2,382.81	410.00	727.84	49.00*	65.88	7.10*	20.05	1,299.10	3,460.63
12	47.00	472.19	220.00	2,390.63	230.00	1,257.61	50.00	167.49	11.00*	65.11	558.00	4,353.02
13	47.00	246.56	55.00	347.31	61.00	117.51	23.00	33.60	5.42*	12.24	191.42	757.22
14	80.00	410.53	28.00*	1,945.78	61.00	125.70	59.00	98.41	10.00*	22.70	238.00	2,603.12
15	320.00	844.63	1,800.00	2,652.70	2,500.00	1,369.21	180.00	187.20	13.20*	45.18	4,813.20	5,098.91
16	210.00	478.91	150.00	2,126.21	1,500.00	1,354.17	73.00	77.84	50.00*	20.64	1,983.00	4,057.77
17	7.10*	204.94	BDL	1,264.98	210.00	1,512.32	BDL	14.14	4.10*	BDL	221.80	2,996.39
18	2.40*	9.71	1.00*	3.29	3.30*	9.41	BDL	4.93	BDL	9.60	6.70	36.94
Average	123.40	373.80	2,374.80	1,638.30	557.10	697.58	85.12	1,594.27	18.77	29.47	3,159.17	4,333.35

*Estimated value
BDL - Below Detection limit.

Table 9-5. (CONTINUED)

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II. Phase II Test Runs

Run test	Dichloroethylene Laboratory	Derived	Trichloroethylene Laboratory	Derived	Tetrachloroethylene Laboratory	Derived	Xylene Laboratory	Derived	Other VOC's Laboratory	Derived	Total VOC's Laboratory	Derived
19	0.75*	2.80	BDL	2.56	BDL	0.13	3.30	10.87	0.53*	7.19	4.58	23.54
20	0.74*	2.59	BDL	1.30	0.40*	BDL	13.00	12.98	2.36*	17.94	16.50	34.81
21	0.02*	BDL	0.07*	0.01	0.03*	BDL	0.16	11.81	0.02*	19.68	0.30	31.50
22	BDL	BDL	BDL	0.17	BDL	0.02	34.00	40.42	5.60	21.72	39.60	62.33
23	BDL	0.01	BDL	0.14	BDL	0.01	1.50	58.00	0.38	33.29	1.88	91.45
24					NO AIR MONITORING							
25					NO AIR MONITORING							
26					NO AIR MONITORING							
27					NO AIR MONITORING							
28					NO AIR MONITORING							

* = Estimated value
BDL = Below Detection Limit

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9.1.1.2 Moisture content. As expected, the moisture content of the feed soil varied with local weather conditions. The average moisture content of the feed soils was 18.7 percent by weight, with a range of 13.8 to 26.4 percent by weight. During Test Runs 27 and 28, previously treated soils from Test Run 2 were processed. The moisture contents of these soils were 10.7 percent by weight and 11.3 percent by weight for feed soils used in Test Runs 27 and 28, respectively.

9.1.1.3 Temperature. The temperature of the feed soils varied from 14.2°C to 31.1°C. The average feed soil temperature was 24.9°C.

9.1.2 Actual air inlet composition/conditions.

9.1.2.1 VOC concentrations. Field instruments were used to monitor the total VOC concentration in the inlet air stream (the detection limit of the field instrument was 1 ppm by volume). At no time during the pilot study were VOC's detected in the inlet air stream.

9.1.2.2 Moisture content. The moisture content of the inlet air stream varied with ambient conditions, time of day, etc. As shown in Table 9-1, the average moisture content of the ambient air was 1.9 percent by weight and ranged from 0.8 percent to 3.0 percent by weight.

9.1.2.3 Ambient temperature. The ambient temperature of the inlet air stream was regularly monitored and recorded. The range of ambient temperatures was from 17°C to 33°C, with an average value of 26.3°C.

9.2 Control test variables. The schedule of test runs as well as a summary of the control test variables are shown in Table 5-1. A brief discussion is included in the following subsections.

9.2.1 Control variables held constant at all levels.

9.2.1.1 Air flow rate. The air flow rate was maintained by setting the position of the damper located on the suction side of the induced draft fan. Although attempts were made to seal the unit, infiltration air was inadvertently drawn through the system. To determine the amount of air infiltrating the system, the flow rate was measured at two separate locations: 1) at the discharge of the air preheater, and 2) at the suction of the induced draft fan. The corresponding flow of infiltration air was determined using the following equation:

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Infiltration Air = Air Discharging the Thermal Processor –
Air Discharging the Preheater

As shown in Table 9-1, the process air flow rate ranged from 102 lbs/hr to 234 lbs/hr, with an average flow rate of 171 lbs/hr. The infiltration air flow rate ranged from 145 lbs/hr to 286 lbs/hr. The average infiltration air flow rate was 215 lbs/hr.

9.2.2 Control variables held constant at various levels.

9.2.2.1 Soil discharge temperature. As mentioned, various levels of soil discharge temperature were maintained during appropriate test runs to evaluate the effect of varying operating temperature on VOC removal efficiency. The operating temperature was maintained by controlling the temperature, pressure, and flow of the heating fluid (i.e., Therminol 66). As the moisture content of the feed soils varied, however, the heat input required to achieve the desired soil discharge temperature also varied, especially when the operating temperature was in close proximity to the boiling point of water. Therefore, the actual soil discharge temperatures varied slightly from the target temperature. The range of actual soil discharge temperatures as well as the average temperatures are shown for Phase I and Phase II test runs in Table 9-1.

9.2.2.2 Soil residence time. The soil residence time was maintained by adjusting the rotational speed of the screws. The range of actual residence times and the average residence times are shown in Table 9-1.

9.2.2.3 Air inlet temperature. Two air inlet temperatures were evaluated during the pilot study: ambient air and heated air. The average ambient air temperature was 24°C, but ranged from 17°C to 29°C, varying with local weather conditions, time of day, etc. For the test runs that operated with an elevated air inlet temperature, the electrical resistance heater was set to the maximum control setting and the corresponding air temperatures were monitored. The temperature of the heated air stream ranged from 61°C to 99°C, with an average value of 90°C.

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9.3 Response variables measured. The average values for the response variables that were measured as well as the range of values are shown in Table 9-1. A brief discussion and more detailed tables are contained in Appendix H and the following subsections.

9.3.1 Processed soil composition/conditions. The response variables measured in the soil discharge stream were the VOC concentrations, moisture content, and mass flow rate. As expected, these response variables were totally dependent on the operating conditions of the specific test runs, i.e., residence time, soil discharge temperature, and air inlet temperature.

9.3.1.1 VOC concentrations. A summary table of the VOC concentrations determined to have been present in the processed soils is included in Table 9-4. These values represent the results of the laboratory GC/MS analyses. The VOC concentrations are presented in a matrix format.

Although the VOC concentrations in the processed soils are very significant, it is not possible to evaluate the effects of soil residence time, soil discharge temperature, and air inlet temperature by simply comparing the residual VOC concentrations. In most cases, the concentration of contaminant in the feed soil had a strong effect on the corresponding concentration in the processed soil. In addition, there were cases where a specific contaminant was not determined to have been present at detectable levels in the feed soil. Therefore, a concentration that is below the detection limit in the processed soil may not reflect complete removal but absence of contaminant in the feed soil. A more effective means of evaluating the operating conditions is to analyze the VOC removal efficiency, i.e.:

VOC Removal Efficiency =

$$\frac{\text{VOC's in Feed Soil} - \text{VOC's in Processed Soil}}{\text{VOC's in Feed Soil}} \times 100 \text{ percent}$$

In this equation, the VOC's in feed soil refer to the "backed out" concentrations discussed in Subsection 9.1.1.1.1. A summary of the VOC removal efficiencies associated with each set of operating conditions is shown in Table 9-5.

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I. Ambient Air Inlet Temperature

Residence Time (Minutes)	Contaminant	Soil Discharge Temperature (°C)			Maximum
		50	100	150	
30	DCE	160.00	BDL	1.10	—
	TCE	880.00	BDL	7.00	—
	PCE	400.00	BDL	29.00	—
	Xylene	64.00	4.10	6.40	—
	Other	12.90	BDL	1.31	—
	Major 4	1504.00	4.10	43.50	—
	Total	1516.90	4.10	44.81	—
45	DCE	BDL	1.90	0.77	—
	TCE	0.01	57.00	0.21	—
	PCE	0.05	1.00	BDL	—
	Xylene	BDL	7.90	0.04	—
	Other	BDL	1.00	1.01	—
	Major 4	0.06	67.80	1.02	—
	Total	0.06	68.80	2.03	—
60	DCE	BDL	BDL	0.51	—
	TCE	BDL	BDL	0.58	—
	PCE	BDL	BDL	0.05	—
	Xylene	BDL	0.01	0.05	—
	Other	BDL	BDL	1.17	—
	Major 4	BDL	0.01	1.19	—
	Total	BDL	0.01	2.37	—
	DCE	0.89	—	—	0.39
	TCE	5.00	—	—	1.90
	PCE	1.30	—	—	0.27
	Xylene	0.13	—	—	0.03
	Other	0.10	—	—	0.17
	Major 4	7.32	—	—	2.59
	Total	7.42	—	—	2.76
	DCE	13.00	—	—	—
	TCE	21.00	—	—	—
	PCE	0.60	—	—	—
	Xylene	0.89	—	—	—
	Other	0.45	—	—	—
	Major 4	43.49	—	—	—
	Total	43.94	—	—	—
	DCE	3.30	—	—	—
	TCE	52.00	—	—	—
	PCE	48.00	—	—	—
	Xylene	5.80	—	—	—
	Other	2.89	—	—	—
	Major 4	109.10	—	—	—
	Total	111.99	—	—	—
75	DCE	—	—	—	—
	TCE	—	—	—	—
	PCE	—	—	—	—
	Xylene	—	—	—	—
	Other	—	—	—	—
	Major 4	—	—	—	—
	Total	—	—	—	—
90	DCE			—	0.09
	TCE			—	0.13
	PCE				BDL
	Xylene			—	BDL
	Other				0.70
	Major 4				0.22
	Total	—			0.92

DCE   Dichloroethylene
TCE   Trichloroethylene
PCE   Tetrachloroethylene
        Phase I Test Runs

BDL   Below Detection Limit
         Not Evaluated
N/A   No VOC's were determined to be present
         in the feed or processed soils

TABLE 9-4   CONCENTRATION OF VOC'S IN THE PROCESSED SOILS (PPM BY WEIGHT)

II. Elevated Air Inlet Temperature

Residence Time (Minutes)	Contaminant	Soil Discharge Temperature (°C)			Maximum
		50	100	150	
30	DCE	0.17	15.00	2.00	—
	TCE	0.23	61.00	12.00	—
	PCE	0.09	33.00	27.00	—
	Xylene	BDL	20.00	7.50	—
	Other	BDL	3.62	1.50	—
	Major 4	0.49	129.00	48.50	—
	Total	0.49	132.62	50.00	—
45	DCE	0.42	BDL	1.30	—
	TCE	0.02	0.06	2.10	—
	PCE	0.08	0.04	1.30	—
	Xylene	0.30	0.04	0.19	—
	Other	0.30	0.07	0.78	—
	Major 4	0.82	0.13	4.89	—
	Total	1.12	0.20	5.67	—
60	DCE	0.67	BDL	0.73	—
	TCE	40.00	6.90	1.80	—
	PCE	320.00	BDL	1.40	—
	Xylene	3.60	BDL	0.55	—
	Other	BDL	BDL	BDL	—
	Major 4	364.27	6.90	4.48	—
	Total	364.27	6.90	4.48	—
	DCE	—	—	BDL	0.24
	TCE	—	—	0.20	0.98
	PCE	—	—	0.03	0.15
	Xylene	—	—	0.05	0.08
	Other	—	—	0.74	1.35
	Major 4	—	—	0.28	1.45
	Total	—	—	1.01	2.80
75	DCE	—	—	—	BDL
	TCE	—	—	—	0.01
	PCE	—	—	—	BDL
	Xylene	—	—	—	0.04
	Other	—	—	—	0.28
	Major 4	—	—	—	0.05
	Total	—	—	—	0.33
90	DCE	—	—	0.01	BDL
	TCE	—	—	0.16	0.01
	PCE	—	—	0.02	BDL
	Xylene	—	—	0.14	0.02
	Other	—	—	1.43	0.53
	Major 4	—	—	0.33	0.03
	Total	—	—	1.76	0.56

DCE	Dichloroethylene	BDL	Below Detection Limit
TCE	Trichloroethylene	—	Not Evaluated
PCE	Tetrachloroethylene	N/A	No VOC's were determined to be present
	Phase I Test Runs		in the feed or processed soils

TABLE 9-4   (CONTINUED)

I. Ambient Air Inlet Temperature

Residence Time (Minutes)	Contaminant	Soil Discharge Temperature (°C)			Maximum
		50	100	150	
30	DCE	46.71	100.00	99.89	—
	TCE	56.41	100.00	99.78	—
	PCE	44.58	100.00	98.27	—
	Xylene	27.89	95.47	97.21	—
	Other	0	100.00	97.64	—
	Major 4	51.94	99.91	99.30	—
	Total	51.73	99.91	99.28	—
45	DCE	N/A	99.69	99.84	—
	TCE	99.96	98.31	99.99	—
	PCE	99.93	98.30	100.00	—
	Xylene	100.00	97.67	99.97	—
	Other	N/A	99.04	96.29	—
	Major 4	99.96	98.46	99.97	—
	Total	99.96	98.47	99.93	—
60	DCE	N/A	100.00	99.81	—
	TCE	N/A	100.00	99.85	—
	PCE	N/A	100.00	99.96	—
	Xylene	N/A	99.94	99.87	—
	Other	N/A	N/A	91.40	—
	Major 4	N/A	100.00	99.86	—
	Total	N/A	100.00	99.72	—
	DCE	96.45	—	—	N/A
	TCE	97.57	—	—	97.97
	PCE	99.19	—	—	99.80
	Xylene	99.37	—	—	99.90
	Other	98.49	—	—	N/A
	Major 4	98.22	—	—	98.98
	Total	98.22	—	—	98.92
	DCE	65.79	—	—	—
	TCE	98.24	—	—	—
	PCE	98.31	—	—	—
	Xylene	97.78	—	—	—
	Other	95.17	—	—	—
	Major 4	97.56	—	—	—
	Total	97.55	—	—	—
	DCE	90.26	—	—	—
	TCE	98.00	—	—	—
	PCE	95.22	—	—	—
	Xylene	97.78	—	—	—
	Other	84.94	—	—	—
	Major 4	97.08	—	—	—
	Total	97.02	—	—	—
75	DCE	—	—	—	—
	TCE	—	—	—	—
	PCE	—	—	—	—
	Xylene	—	—	—	—
	Other	—	—	—	—
	Major 4	—	—	—	—
	Total	—	—	—	—
90	DCE	—	—	—	98.87
	TCE	—	—	—	99.97
	PCE	—	—	—	100.00
	Xylene	—	—	—	100.00
	Other	—	—	—	90.52
	Major 4	—	—	—	99.98
	Total	—	—	—	99.91

DCE   Dichloroethylene
TCE   Trichloroethylene
PCE   Tetrachloroethylene
⬜   Phase I Test Runs

BDL   Below Detection Limit
-   Not Evaluated
N/A   No VOC's were determined to be present in the feed or processed soils

TABLE 9-5   REMOVAL EFFICIENCY OF VOC'S (PERCENT)

II. Elevated Air Inlet Temperature

Residence Time (Minutes)	Contaminant	Soil Discharge Temperature (°C)			Maximum
		50	100	150	
30	DCE	0	98.52	99.66	—
	TCE	99.27	97.32	99.60	—
	PCE	0	91.65	98.30	—
	Xylene	100.00	83.61	96.45	—
	Other	N/A	91.85	98.17	—
	Major 4	98.77	96.62	99.10	—
	Total	98.77	96.56	99.09	—
45	DCE	96.20	N/A	99.54	—
	TCE	99.41	0	99.92	—
	PCE	99.26	99.53	99.83	—
	Xylene	94.65	0	99.73	—
	Other	97.29	0	96.37	—
	Major 4	97.36	98.31	99.87	—
	Total	97.34	97.47	99.85	—
60	DCE	99.89	100.00	99.90	—
	TCE	98.89	99.85	99.95	—
	PCE	89.91	100.00	99.92	—
	Xylene	85.95	100.00	100.00	—
	Other	100.00	100.00	100.00	—
	Major 4	95.09	99.90	99.99	—
	Total	95.10	99.90	99.99	—
	DCE	—	—	0	92.71
	TCE	—	—	0	67.48
	PCE	—	—	0	0
	Xylene	—	—	99.89	99.34
	Other	—	—	97.11	84.11
	Major 4	—	—	99.42	92.45
	Total	—	—	98.61	89.90
75	DCE	—	—	—	0
	TCE	—	—	—	0
	PCE	—	—	—	0
	Xylene	—	—	—	99.76
	Other	—	—	—	98.88
	Major 4	—	—	—	99.68
	Total	—	—	—	99.18
90	DCE	—	—	0	100.00
	TCE	—	—	0	99.54
	PCE	—	—	0	0
	Xylene	—	—	99.79	99.84
	Other	—	—	96.29	97.50
	Major 4	—	—	99.52	99.84
	Total	—	—	98.34	98.63

DCE   Dichloroethylene   BDL   Below Detection Limit
TCE   Trichloroethylene   —   Not Evaluated
PCE   Tetrachloroethylene   N/A   No VOC's were determined to be present
    Phase I Test Runs   in the feed or processed soils.

TABLE 9-5 (CONTINUED)

9.3.1.2 Moisture content. The moisture content in the processed soil varied with changes in the operating conditions. The moisture content of the processed soils is shown, in matrix format, for all operating conditions in Table H-1 in Appendix H.

9.3.1.3 Mass flow rate. The mass flow rates of the feed and processed soils were monitored regularly during the pilot study. As expected, the mass flow rate of the processed soils varied with changes in the operating conditions and moisture content in the soil. The mass flow rates of the feed and processed soil streams are summarized in Table H-2 in Appendix H.

9.3.2 Actual air discharge composition/conditions. The composition/condition of the discharge air stream was monitored at two locations: 1) at the suction side of the afterburner inlet during appropriate test runs; and 2) in the afterburner stack during three selected test runs (i.e., Test Runs 8, 9, and 10). The data collected for each location will be presented separately.

9.3.2.1 Afterburner inlet.

9.3.2.1.1 VOC concentrations. VOC concentrations were monitored via modified VOST trains at the afterburner inlet during the first 18 test runs. In addition, to identify and quantify the VOC's that were being removed along the length of the processor, modified VOST trains were also used to sample the air streams in manifolds 1, 2 and 3 during Test Runs 19 through 23. The VOC concentrations determined to be present in the afterburner inlet and in the three legs of the manifolds are shown in Table 9-6. Those concentrations are based on the results of the GC/MS analyses, using the VOST train.

In addition to the laboratory GC/MS analyses, two other modes of analysis were used to analyze the discharge gas in the three legs of the manifold system: 1) a CEM system, and 2) a mobile mass spectrometer. These instruments were used to obtain a real-time estimate of VOC emissions from the thermal processor. A brief discussion of these modes of analysis and a summary of the data determined using these instruments are contained in Tables H-3 through H-6 in Appendix H.

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I. Ambient Air Inlet Temperature

Residence Time (Minutes)	Contaminant	Soil Discharge Temperature (°C)			Maximum
		50	100	150	
30	DCE	24.20	82.00	121.00	—
	TCE	145.00	270.00	281.00	—
	PCE	32.50	136.00	112.00	—
	Xylene	3.60	11.00	24.00	—
	Other	BDL	3.60	6.00	—
	Major 4	205.30	499.00	538.00	—
	Total	205.30	502.60	544.00	—
45	DCE	BDL	196.00	52.00	—
	TCE	1.70	785.00	183.00	—
	PCE	3.00	11.00	9.20	—
	Xylene	3.00	97.00	11.00	—
	Other	BDL	32.80	2.80	—
	Major 4	7.70	1089.80	255.20	—
	Total	7.70	1121.80	258.00	—
60	DCE	BDL	20.00	35.00	—
	TCE	BDL	90.00	37.00	—
	PCE	BDL	85.00	9.80	—
	Xylene	BDL	1.10	4.20	—
	Other	BDL	BDL	1.60	—
	Major 4	BDL	196.10	86.00	—
	Total	BDL	196.10	87.60	—
75	DCE	—	—	—	—
	TCE	—	—	—	—
	PCE	—	—	—	—
	Xylene	—	—	—	—
	Other	—	—	—	—
	Major 4	—	—	—	—
	Total	—	—	—	—
90	DCE	—	—	—	—
	TCE	—	—	—	—
	PCE	—	—	—	—
	Xylene	—	—	—	—
	Other	—	—	—	—
	Major 4	—	—	—	—
	Total	—	—	—	—

DCE   Dichloroethylene
TCE   Trichloroethylene
PCE   Tetrachloroethylene
          Phase I Test Runs

BDL   Below Detection Limit
—   Not Evaluated
N/A   No VOC's were determined to be present in the feed or processed soils

TABLE 9-6   VOC CONCENTRATIONS IN THE AIR DISCHARGE STREAM AT THE AFTERBURNER INLET AS DETERMINED BY GC/MS (PPM BY VOLUME)

II. Elevated Air Inlet Temperature

Residence Time (Minutes)	Contaminant	Soil Discharge Temperature (°C)			
		50	100	150	Maximum
30	DCE	BDL	173.00	63.00	—
	TCE	4.40	283.00	238.00	—
	PCE	BDL	36.60	97.00	—
	Xylene	1.50	15.80	20.00	—
	Other	BDL	7.40	8.50	—
	Major 4	5.90	508.40	418.00	—
	Total	5.90	515.80	426.50	—
45	DCE	1.70	BDL	54.00	—
	TCE	0.40	BDL	362.00	—
	PCE	1.00	1.10	87.00	—
	Xylene	1.00	BDL	12.00	—
	Other	1.20	BDL	3.80	—
	Major 4	4.10	1.10	515.00	—
	Total	5.30	1.10	518.80	—
60	DCE	87.00	208.00	75.00	—
	TCE	375.00	567.00	254.00	—
	PCE	237.00	76.70	106.00	—
	Xylene	3.00	60.00	3184.00	—
	Other	2.00	24.70	4.70	—
	Major 4	702.00	911.70	3619.00	—
	Total	704.00	936.40	3623.70	—

Residence Time (Minutes)	Contaminant	50	100	150			Maximum		
				Man 1	Man 2	Man 3	Man 1	Man 2	Man 3
60	DCE	—	—	BDL	BDL	BDL	0.50	0.60	0.50
	TCE	—	—	BDL	BDL	BDL	BDL	0.30	0.30
	PCE	—	—	BDL	BDL	BDL	BDL	BDL	BDL
	Xylene	—	—	2.50	8.10	2.40	1.30	1.90	2.20
	Other	—	—	1.10	5.30	1.20	0.60	0.80	2.20
	Major 4	—	—	2.50	8.10	2.40	1.80	2.80	3.00
	Total	—	—	3.60	13.40	3.60	2.40	3.60	5.20
75	DCE	—	—	—			BDL	BDL	BDL
	TCE	—	—	—			BDL	BDL	BDL
	PCE	—	—	—			BDL	BDL	BDL
	Xylene	—	—	—			0.80	1.50	2.10
	Other	—	—	—			0.80	2.00	5.50
	Major 4	—	—	—			0.80	1.50	2.10
	Total	—	—	—			1.60	3.50	7.60
90	DCE	—	—	BDL	BDL	BDL	0.40	0.50	BDL
	TCE	—	—	BDL	BDL	BDL	BDL	0.30	BDL
	PCE	—	—	BDL	BDL	BDL	BDL	BDL	BDL
	Xylene	—	—	6.50	6.00	2.60	1.10	1.80	1.30
	Other	—	—	4.30	3.60	1.20	0.50	1.60	4.00
	Major 4	—	—	6.50	6.00	2.60	1.50	2.60	1.30
	Total	—	—	10.80	9.60	3.80	2.00	4.20	5.30

DCE Dichloroethylene
TCE Trichloroethylene
PCE Tetrachloroethylene
Phase I Test Runs

BDL Below Detection Limit
— Not Evaluated
N/A No VOC's were determined to be present in the feed or processed soils

TABLE 9-6 (CONTINUED)

During optimization runs 24 through 28, the air discharge stream was not monitored via modified VOST trains. The evaluation of test run conditions was based solely on samples of the feed and processed soils. However, in order to obtain a real-time estimate of VOC emissions, a CEM system was used to monitor manifold number 2 during Test Runs 25 through 28. (The portable monitor was non-functional during Test Run 24).

9.3.2.1.2 Moisture content. The moisture content of the air discharge stream was monitored at the afterburner inlet. The moisture content of the combined air stream is shown for all operating conditions in Table H-7 in Appendix H.

9.3.2.1.3 Temperature. The temperature of the gases discharging the thermal processor were monitored during each test run. Temperatures were monitored in each leg of the manifold system as well as at the afterburner inlet. Air discharge temperatures are summarized in Table H-8 in Appendix H.

9.3.2.2 Afterburner outlet. In accordance with an agreement with PADER, the gases discharging the afterburner were monitored during three selected test runs, Test Runs 8, 9, and 10. The operating conditions of the three test runs represented a low, medium, and high VOC-inlet loading condition at the afterburner. The stack gases were monitored for VOC's, particulate, hydrochloric acid, and fixed gases (i.e., carbon dioxide, oxygen, carbon monoxide). A summary of pertinent data is contained in Table 9-7. Detailed data is included in Appendix F.

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TABLE 9-7. SUMMARY OF STACK TESTING RESULTS

Description	Test Run 8	Test Run 9	Test Run 10
Test Date	8/13/85	8/14/85	8/15/85
Test Duration, minutes	203	197	180
Process Conditions:			
- Target Soil Residence Time, minutes	30	30	60
- Target Processed Soil Temperature, °C	50	100	150
- Inlet Air Conditions	Ambient	Heated	Heated
VOC's in Afterburner Inlet Stream (ppm/volume)	205.3	515.8	3623.7
Stack Gas Composition:			
- CO_2, % by volume, dry basis	7.0	7.4	7.7
- O_2, % by volume, dry basis	10.6	9.4	9.0
- CO, % by volume, dry basis	0.0	0.0	0.0
- N_2, % by volume, dry basis	82.4	83.2	83.3
- Water Vapor, % by volume	13.7	24.8	17.6
Stack Gas Temperature, °C	1,016	999	977
Stack Gas Temperature, °F	1,860	1,830	1,790
Stack Gas Flow Rate, acfm, wet basis	602	598	553
Stack Gas Flow Rate, scfm, dry basis	116	102	104
Stack Gas Emission Rates			
- Particulates, lbs/hr	0.041	0.021	0.032
- Particulates, gr/dscf at 12% CO_2	0.071	0.040	0.060
- Hydrogen Chloride, ppm by volume	1,140	3,107	2,620
- Hydrogen Chloride, lbs/hr	0.75	1.80	1.55

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TABLE 9-7. (continued)

Description	Test Run 8	Test Run 9	Test Run 10
VOC's in stack gas (ppm/volume)			
Dichloroethylene	<0.0002	<0.0002	<0.0002
Trichloroethylene	<0.0003	<0.0003	<0.0003
Tetrachloroethylene	<0.0002	<0.0002	<0.0002
Xylene	<0.0003	<0.0003	<0.0003

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10. ANALYSIS OF RESULTS

10.1 Statistical correlations.

10.1.1 Analytical technique for developing equations. In the early stages of the project, a test plan[4] was developed that identified key process variables and established a matrix of test conditions (replicated for two different inlet air temperatures). This experimental design was selected to allow statistical evaluation of the data. Multiple linear regression[6] was employed as the statistical analysis of variance (ANOVA) technique. The analytical approach is outlined in Appendix I.

The objective of the analytical approach was to apply the multiple linear regression technique to combinations of the data base independent, control, and reponse variables to develop simple linear equations of the type:

$$Y = b_o + b_1 x_1 + \ldots + b_n x_n + E$$

where:

Y = response variable
b_o = intercept
$b_1 \ldots b_n$ = regression coefficients
$x_1 \ldots x_n$ = input or controlled variables
E = residuals

The equations would identify those input or controlled variables that had a greater significant impact on the response variable of concern; in this case, the concentration of total VOC's in the processed soils. The method of statistical interpretation was as follows:

1. Identified response, input, and control variables.
2. Identified data base.
3. Reviewed data base to identify and exclude data outliers.
4. Applied the multiple linear regression technique to the entire data base (i.e., every test run, regardless of difference in operating conditions).
5. When Step 4 was unsuccessful, separated data base into subgroups based on soil discharge temperature.

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6. Applied the multiple linear regression technique to the subgrouped data.
7. Developed simple linear equations for design of a full-scale system.
8. Inserted actual data into the appropriate equations to confirm their validity.

10.1.1.1 Identification of response, input, and control variables. The objective of employing the multiple linear regression technique was to develop correlations that would support design of a full-scale system In most cases, if not all cases, design of a full-scale system would be based upon the level of treatment required to achieve a target VOC concentration in the processed soils. The target concentration would most likely be based upon regulatory criteria, or, if nonexistent, negotiations with regulatory agencies. Therefore, the response variable of interest was identified to be the total VOC concentration in the processed soils.

The remainder of the variables were broken down into two groups: 1) those variables that are independent, site-specific, and usually known prior to design of a system (i.e. input variables); and 2) those variables that are critical design parameters and, thus, directly affect system economics (i.e. control variables). The input and control variables were identified to be:

1. Input Variables
    a. Moisture content of the feed soil (percent by weight).
    b. Total VOC concentration in the feed soil (#/hr).
2. Control Variables
    a. Heat rate (Btu/hr).
    b. Residence time (minutes).
    c. Flow rate of air (#/hr).

Note that temperature of the inlet air stream was not identified as a control variable. Upon review of the VOC removal efficiencies listed in Table 9-5, it was evident that an elevated air inlet temperature did not improve thermal stripping. In fact, in most cases the VOC removal efficiences associated with the elevated air inlet temperature were actually lower than those associated with an ambient air inlet temperature.

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10.1.1.2 Identification of data base. Originally, only the data from Phase I of the pilot investigation was designated for statistical evaluation, as there were two replications for each operating condition (i.e. ambient and elevated air inlet temperatures). However, since the operating conditions of Test Runs 24, 25, and 26 of Phase II were identical to those of Test Run 1, the data from these three runs were also included in the data base.

10.1.1.3 Identification of data outliers. The data base was reviewed to identify data outliers. The following data was excluded from the data base:

1. All data pertaining to Test Run 1. No detectable levels of VOC were determined to be present in the processed soil or discharge air stream.

2. All data pertaining to Test Run 2. The trichloro-ethylene concentration in the VOST tube was not quantified. The trichloroethylene peak on the GC/MS spectrum was reported to be out of the calibration range but not saturated. The mass of trichloroethylene in the VOST tube was reported to be greater than 70,000 micrograms.

3. All data pertaining to Test Run 4. The VOC concentra-tions in the discharge air stream were below the detection limit.

4. Test Run 3 - dichloroethylene and other VOC's; Test Run 7 - Other VOC's; Test Run 17 - Other VOC's. These contaminants were not present at detectable levels in the processed soil or discharge air stream.

5. Test Run 7 - dichloroethylene and tetrachloroethylene. The concentrations of dichloroethylene and tetrachloroethylene were below the detection limits in the air stream and only slightly above the detection limit in the processed soils.

10.1.1.4 Application of multiple linear regression techniques. Originally, multiple linear regression techniques were applied to the entire data base using the previously identified response, input, and control variables. Initial attempts to develop correlations failed. Anticipating that an exponential relationship may exist, the data was transformed, and the data base was modified to include those values corresponding to the natural logarithm of total VOC's in the processed soil. However, transformation of the data base proved insufficient; attempts to develop correlations still failed.

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The next approach was to separate the data base into subgroups based on the soil discharge temperature (i.e. low, medium, and high temperature test runs). When broken down into subgroups, attempts to develop correlations were successful. Simple linear equations, which were statistically significant, were developed for design of a full-scale system operating at low, medium, or high soil discharge temperatures.

Since the correlations were applicable to three distinct soil discharge temperature ranges, multiple linear regression techniques were also employed to identify the variables that were significant to the processed soil temperature. Simple equations were developed to estimate the soil discharge temperature for a system operating at high temperatures medium and high temperature ranges. No equation was developed for the low or medium temperature runs because there was too much variance in the data associated with heat input to the system under these conditions. The significant input variables identified were moisture in the feed soil and flow rate of inerts. The significant control variables were identified to be heat rate, moisture in the processed soil, and soil residence time.

10.1.2 Presentation of correlations. The correlations corresponding to the low, medium, and high soil discharge temperatures will be presented and discussed separately. The following legend is applicable to all equations:

TOT VOC's$_{PS}$	=	Total VOC concentrations in the processed soil (#/hr).
TOT VOC's$_{FS}$	=	Total VOC concentrations in the feed soil (#/hr).
H	=	Heat rate (Btu/hr).
T_R	=	Residence Time (minutes).
F_A	=	Flow Rate of Air (#/hr) – includes process and infiltration air.
M_{PS}	=	Moisture in the processed soil (percent by weight).
M_{FS}	=	Moisture in the feed soil (percent by weight).
Temp$_{PS}$	=	Temperature of the processed soil ($^{\circ}$C).
F_I	=	Flow Rate of Inerts, i.e., non-volatiles (feed soil minus VOC's/moisture) (#/hr).

10.1.2.1 Low temperatures. Although the target soil discharge temperature was 50°C, the actual soil discharge temperature varied slightly. Therefore, the equations presented in this subsection are not restricted to a 50°C soil discharge temperature but are applicable within the range of 49.7°C to 66.3°C.
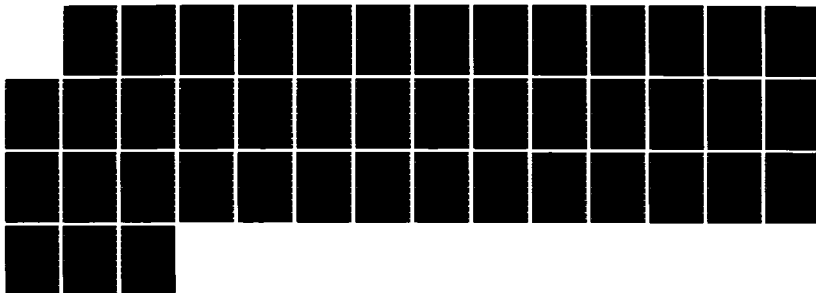
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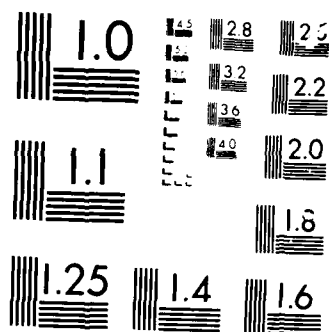
10.1.2.1.1 VOC concentration in the processed soil. The correlation for estimating the total VOC concentration in the processed soil for a system operating at low temperatures is as follows:

$$\ln [\text{TOT VOC's}_{PS}] = -47.925 + (9.5717 * \text{TOT VOC's}_{FS})$$

$$+ (0.847 * M_{FS}) - (0.0904 * T_R)$$

$$+ (0.0649 * F_A)$$

It must be emphasized that this equation is only applicable if the response, input, and control variables are within the following ranges:

TEMP$_{PS}$:   49.7 - 66.3 ("C)

TOT VOC's$_{FS}$:   0.00791 - 0.7617 (#/hr) (i.e., 40-3,890 ppm)

M$_{FS}$:   16.4 - 20.6 (Percent by weight)

T$_R$:   29.70 - 58.57 (minutes)

F$_A$:   356 - 464 (#/hr)

H: 11,624 - 47,765 (Btu/hr)

Even though heat rate is not determined to be significant in the correlation, its range of values (i.e. 11,624 Btu/hr to 47,765 Btu/hr) must be observed. Since actual total VOC concentrations in the processed soil resulted from a system that operated within the corresponding heat rate range, its presence in the equation is implied. The fact that the heat rate is not contained in the equation, however, suggests that there is not a strong correlation between the VOC concentration in the processed soil and the heat input to the system at low temperatures.

10.1.2.1.1.1 Analysis of the regression coefficients. Analysis of the regression coefficients in the equation gives an indication of the relative importance of each of the input or control variables. A positive regression coefficient implies that the VOC concentration in the processed soil increases as the value of the input or control variable increases. The reverse is true for variables with a negative regression coefficient.

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As expected, the VOC concentration in the feed soils has a positive regression coefficient. Obviously, for fixed operating conditions, an increase in the feed concentration would result in a higher concentration in the processed soil.

The equation also indicates that an increase in the moisture content of the feed soil would result in an increase in the VOC concentration of the processed soils. The explanation for this phenomena may be twofold. First, since VOC's are soluble in water, a higher moisture content could contain a greater amount of VOC's in solution and, thus, result in a feed soil with a higher concentration. As mentioned above, under fixed operating conditions a higher feed concentration would result in a higher processed soil concentration. Second, if more moisture is present in the soils, the heat input to the system may be absorbed by the moisture and not contribute to VOC volatization.

The regression coefficient of residence time is negative, as expected, suggesting the obvious: an increase in treatment time, under fixed operating conditions, would result in a lower VOC concentration in the processed soil.

An unexpected phenomena corresponds to the air flow rate. It seems intuitive that in a thermal stripping process, an increase in the flow rate of air would result in greater stripping and enhanced volatization. The regression coefficient, however, suggests just the opposite; an increase in the air flow rate would result in an increased VOC concentration in the processed soil. This may be due to the fact that inherent in the term "thermal stripping," temperature plays a major role. Obviously, under fixed operating conditions, an increased air flow rate would absorb an increased amount of heat. This may result in a lower effective operating temperature and reduce the volatization rate.

10.1.2.1.1.2 Testing the validity of the equation. Actual data from the low temperature test runs were inserted into the equation to test its validity. A summary of actual values of the natural logarithm of the total VOC's in the processed soil is shown on Table 10-1. For comparison, listed also are the estimated values which resulted when the actual data from the appropriate test run was inserted into the equation. As shown, the estimated values exhibited an average deviation (i.e. 100% x (1 - estimated/actual)) from the actual values of 2.51 percent. The range of deviation was from 0.45 percent to 8.08 percent).

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TABLE 10-1.   COMPARISON OF ACTUAL AND ESTIMATED VALUES FOR
              THE NATURAL LOG OF THE TOTAL VOC CONCENTRATION
              IN THE PROCESSED SOIL - LOW TEMPERATURES

Test run	ln [TOT VOC's]$_{PS}$ (actual)	ln [TOT VOC's]$_{PS}$ (estimated)	Deviation between actual and estimated (percent)
3	-11.737	-11.630	0.92
7	-8.990	-9.780	8.08
8	-1.009	-0.985	2.44
18	-8.467	-8.505	0.45
24	-6.970	-7.069	1.40
25	-4.953	-4.710	1.05
26	-4.175	-4.314	3.22
		Average	2.51

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A graphical presentation of actual versus estimated values is shown in Figure 10-1. Also displayed are isoconcentration lines representing the low, medium, and high values of actual feed concentrations (i.e. 40 ppm, 1,960 ppm, and 3,890 ppm). The equation is valid within the region bounded by the upper and lower boundary lines. These lines were developed by inserting the minimum and maximum values, where appropriate, of each of the input and control variables and solving for the natural logarithm of the total VOC's in the processed soil.

10.1.2.1.2 Temperature of the processed soils. Attempts to develop a statistically significant equation to estimate the temperature of the processed soil were not successful. There was too much variance in the data corresponding to the low temperature runs, specifically heat rate.

10.1.2.2 Middle temperatures. The target soil discharge temperature for the middle temperature runs was 100°C. The actual temperature ranged from 95.4°C to 120.9°C. Since the equation was developed using actual values, the correlation is valid within this temperature range.

10.1.2.2.1 Total VOC concentration in the processed soil. The equation for predicting the natural logarithm of total VOC's in the processed soil for a system operating at middle temperatures is:

$$\ln [\text{TOT VOC's}]_{PS} = -18.7913 - (0.0569 * T_R)$$

$$- (8.04 \times 10^{-6} * H) + (5.3553 * \text{TOT VOC's}_{FS})$$

$$+ (0.5112 * M_{FS})$$

This equation is only applicable if the variables are within the following ranges:

TEMP$_{PS}$:   95.4 - 120.9 (°C)
TOT VOC's$_{FS}$: 0.424 - 1.481 (#/hr) (i.e., 1,750 ppm - 6,120 ppm)
M_{FS}:   13.8 - 26.4 (Percent by weight)
T_R: 29.29 - 61.24 (minutes)
F_A: 300 - 440 (#/hr)
H: 90,234 - 457,029 (Btu/hr)

In spite of the fact that air flow rate is not contained in the correlation, the above equation is only applicable within the range noted (i.e. 300-440 #/hr). There does not appear to be a strong correlation between concentration of VOC's in the processed soil and the air flow rate within the noted range.
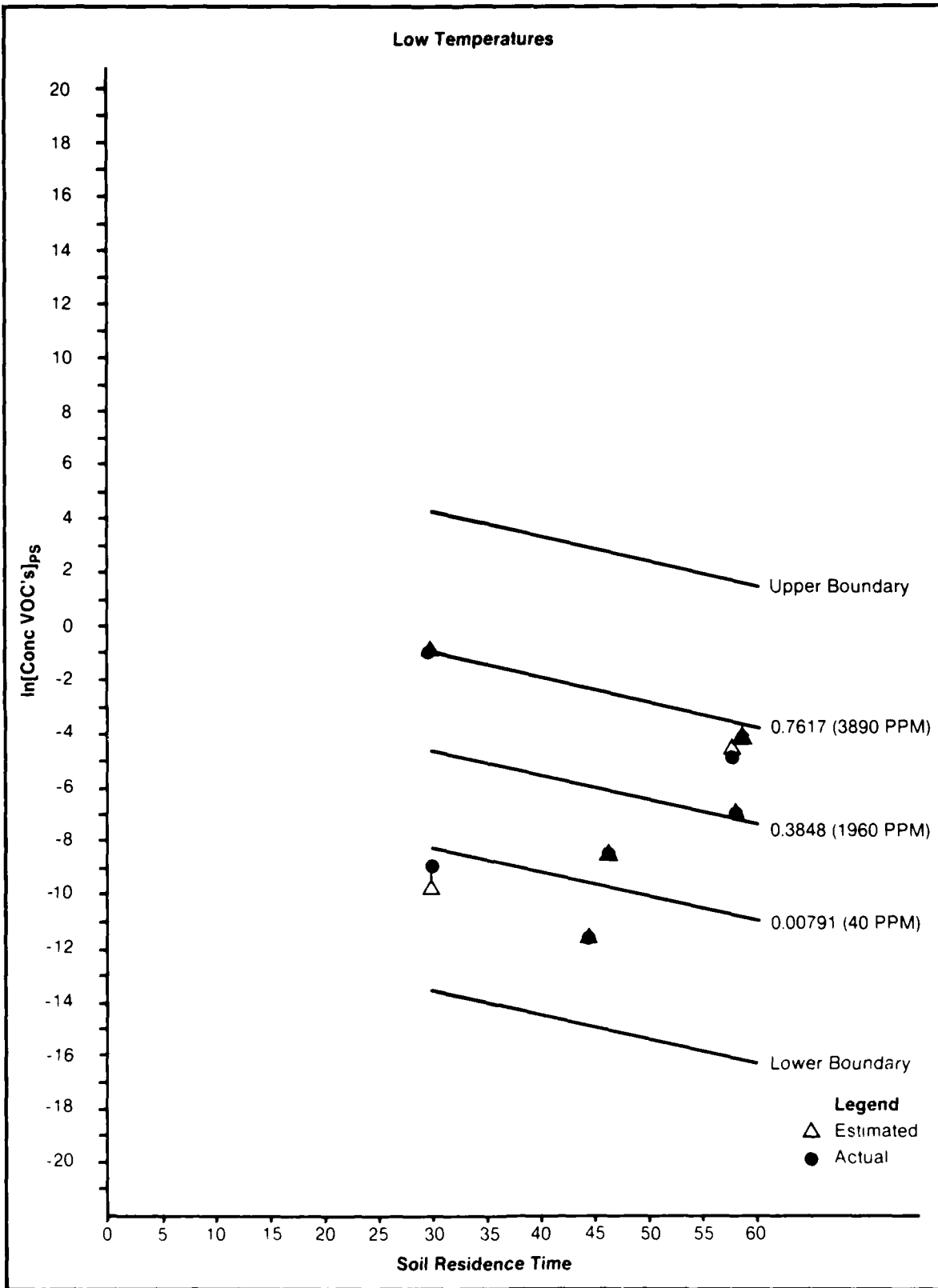
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FIGURE 10-1   COMPARISON OF ACTUAL VERSUS ESTIMATED VALUES
OF THE NATURAL LOGARITHM OF TOTAL VOC'S IN THE
PROCESSED SOIL - LOW TEMPERATURE RUNS

10.1.2.2.1.1 Analysis of the regression coefficients. As mentioned, the regression coefficients indicate the relative contribution of each of the input and control variables. The regression coefficients of the residence time and heat rate are both negative values. This implies that as the treatment time and heat input to the system are increased, the VOC concentration in the processed soil would decrease accordingly.

The regression coefficients of the feed concentration and feed moisture content are positive values. This is consistent with the correlation developed for the low temperature runs discussed in Subsection 10.1.2.1.1.1.

10.1.2.2.1.2 Testing the validity of the equation. Actual values from the appropriate test runs were plugged into the equation to test its validity. For comparison, the actual values of the natural logarithm of total VOC's in the processed soil is shown along with the estimated values in Table 10-2. As shown, the deviation between the actual and estimated values is within the range of 0.01 percent to 0.32 percent. The average deviation between actual and estimated values is 0.09 percent. For illustration, the actual and estimated values are shown in Figure 10-2, as well as isoconcentration lines corresponding to the low, mid, and high VOC feed concentrations (i.e., 1,750 ppm, 3,940 ppm, and 6,120 ppm). The equation is only valid with the region bounded by the upper and lower limit lines. These lines were generated by inserting the minimum or maximum values of the variables, within the noted ranges, into the equation.

10.1.2.2.1.3 Temperature of the processed soils. An equation was not developed to estimate the temperature of the processed soil when operating at middle temperatures. Attempts resulted in an equation which was highly suspect. The equation indicated that the temperature of the processed soil would increase with an increase in the moisture content. However, comparison of actual test data indicated that just the opposite was true, as intuitively expected. In actuality, the temperature of the processed soil increased with decreasing moisture content in the processed soil. The equation was determined to be invalid.

10.1.2.3 High temperatures. The equations developed for the high temperature runs are valid for soil discharge temperatures betwen 137.3"C and 175.3"C.

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TABLE 10-2.   COMPARISON OF ACTUAL AND ESTIMATED VALUES FOR
THE NATURAL LOG OF THE TOTAL VOC CONCENTRATION
IN THE PROCESSED SOIL - MIDDLE TEMPERATURES

Test run	ln [TOT VOC's]$_{PS}$ (actual)	ln [TOT VOC's]$_{PS}$ (estimated)	Deviation between actual and estimated (percent)
5	-6.738	-6.741	0.04
6	-3.803	-3.791	0.32
9	-3.649	-3.651	0.05
16	-7.067	-7.068	0.01
17	-13.673	-13.676	0.02
		Average	0.09

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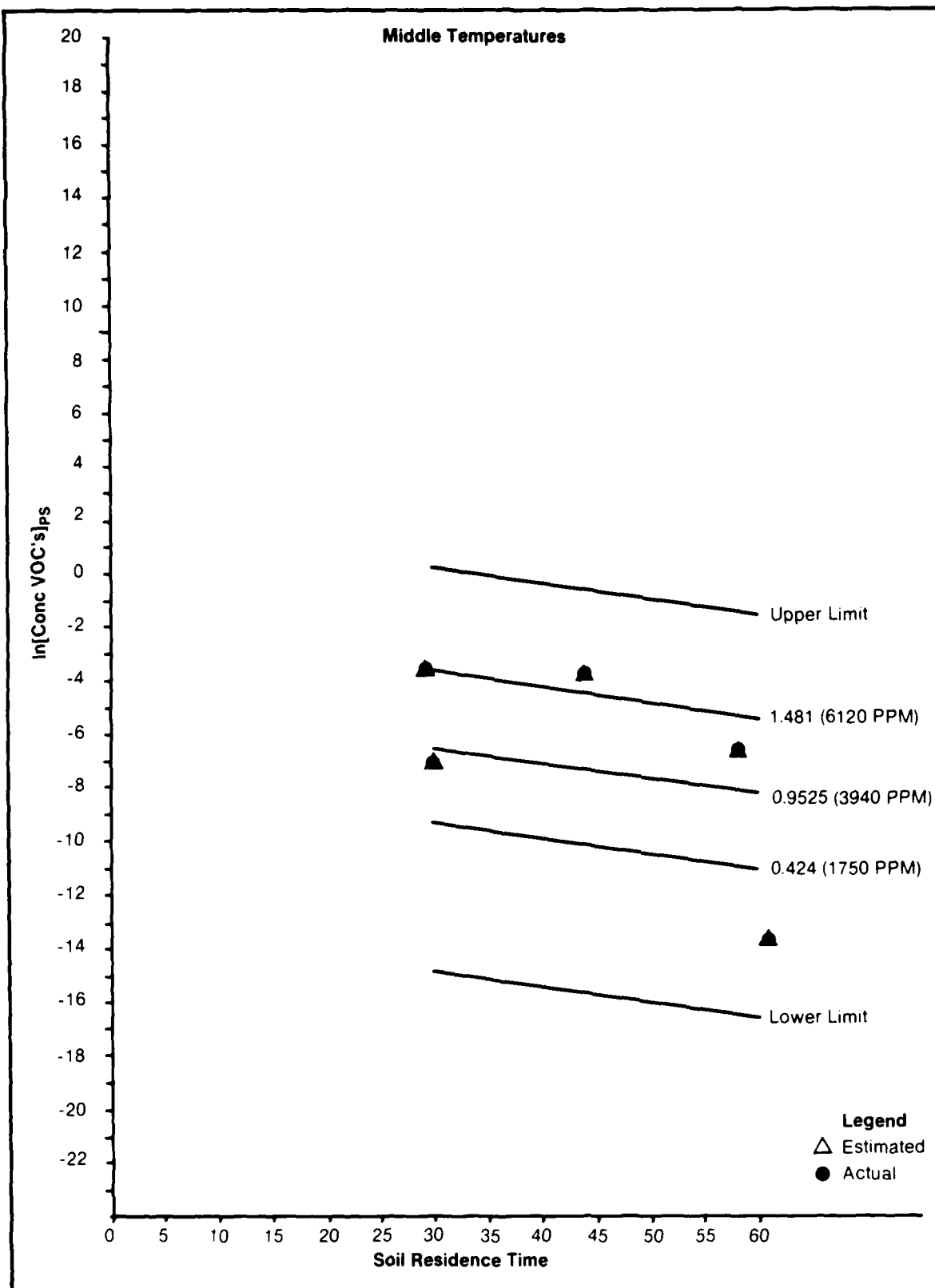FIGURE 10-2   COMPARISON OF ACTUAL VERSUS ESTIMATED VALUES
OF THE NATURAL LOGARITHM OF TOTAL VOC'S IN THE
PROCESSED SOIL - MIDDLE TEMPERATURE RUNS

10.1.2.3.1 Total VOC concentration in the processed soil. The equation developed to estimate the natural logarithm of the total VOC's in the processed soil for a system operating a high temperatures is:

$$\ln \text{[TOT VOC's]}_{PS} = 1.5843 - (3.212 \times 10^{-5} * H)$$

$$+ (0.2784 * M_{FS}) - (0.1993 * T_R)$$

This equation is only valid for input and control variables within the following ranges:

TOT VOC's$_{FS}$:   0.135 - 4.651 (#/hr) (i.e., 757 ppm - 31,923 ppm)
M_{FS}:   15.5 - 20.6 (Percent by weight)
T_R: 28.93 - 60.2 (minutes)
F_A: 316 - 430 (#/hr)
H: 55,326 - 206,412 (Btu/hr)

The feed concentration and flow rate of air are not contained in the equation; however, the equation is only valid within the noted ranges.

10.1.2.3.1.1 Analysis of the regression coefficients. As expected, the estimated concentration in the processed soils decreases as the heat rate and residence time increase. Obviously, the higher the level of treatment, the lower the residual VOC concentration. As in the case of low and middle temperature test runs, the regression coefficient for the moisture in the feed soil is positive. As previously discussed, a higher moisture content has the potential to contain a higher concentration of VOC's in solution. Also, for fixed operating conditions, the heat input to the system may be absorbed by the moisture, thus decreasing the VOC volatization rate. Unexpectedly, the concentration of VOC's in the feed soil was not determined to be a significant factor in the equation. Absence of this factor cannot be attributed to low, insignificant amounts of contaminant in the feed soil as the feed concentrations were relatively high (i.e., average feed concentration of 9,640 ppm total VOC's). Possibly the feed concentration is not a highly significant factor because the operating temperature of the system (i.e., 150°C) was much higher than the boiling point of the major contaminants (i.e., Dichloroethylene - 49°C, trichloroethylene - 87°C, Porchloroethylene - 121°C, and xylene - 144°C).

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10.1.2.3.1.2 Testing the validity of the equation. Actual values of the input and control variables were inserted into the equation to solve for the estimated values of the natural logarithm of the total VOC's in the processed soil. The estimated as well as the actual values are shown in Table 10-3. The average deviation between the actual and estimated values was 2.46, as shown in Table 10-3. The range of deviation was from 0.01 percent to 4.78 percent.

For illustration, the actual and estimated values of the natural logarithm of total VOC's in the processed soil is shown in Figure 10-3. Also included on this graph are constant heat rate lines corresponding to the low, medium, and high heat input to the system (i.e., 55,326 Btu/hr, 130,869 Btu/hr, and 206,412 Btu/hr, respectively). As shown, the equation is valid in the region bounded by the upper limit and lower limit. The upper and lower limits were derived from inserting the minimum and/or maximum values of the input and control variables into the equation and solving for concentration in the processed soils.

10.1.2.3.2 Temperature of the processed soil. The equation developed for estimating the temperature of the processed soil for a system operating at high temperatures is:

$$\text{TEMP}_{PS}: 324.9714 + (6.107 \times 10^{-3} * H) - (6.4424 * M_{FS})$$

$$- (18.0114 * M_{PS}) - (0.326 * F_1)$$

The equation is valid for a system operating with variables whose values are within the following ranges only:

H:	55,325 - 206,411 (Btu/hr)
M_{FS}:	15.5 - 20.6 (Percent by weight)
M_{PS}:	0.1 - 2.0 (Percent by weight)
F_1:	110.54 - 242.27 (#/hr)
T_R:	28.93 - 60.2 (minutes)

10.1.2.3.2.1 Analysis of the regression coefficients. The regression coefficient of heat rate is positive, indicating that the higher the heat input, the higher the temperature of the processed soil.

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TABLE 10-3. COMPARISON OF ACTUAL AND ESTIMATED VALUES FOR
THE NATURAL LOG OF THE TOTAL VOC CONCENTRATION
IN THE PROCESSED SOIL - HIGH TEMPERATURES

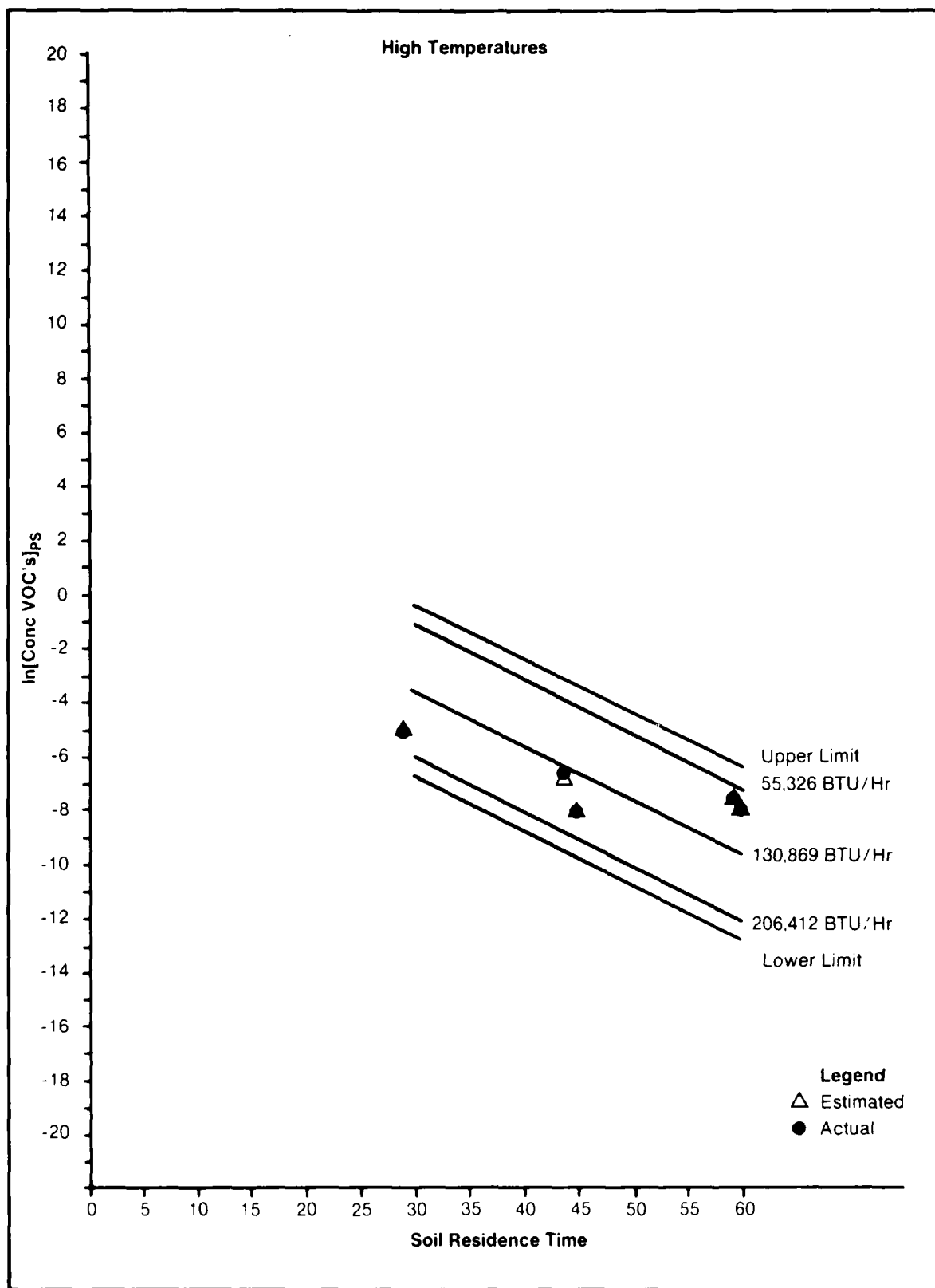| Test run	ln [TOT VOC's]$_{PS}$ (actual)	ln [TOT VOC's]$_{PS}$ (estimated)	Deviation between actual and estimated (percent)
10	-7.584	-7.505	1.05
11	-6.588	-6.881	4.26
12	-5.178	-4.942	4.78
13	-7.876	-7.875	0.01
14	-8.079	-7.934	1.83
15	-5.017	-5.164	2.85
		Average	2.46

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High Temperatures

FIGURE 10-3 COMPARISON OF ACTUAL AND ESTIMATED VALUES OF THE
NATURAL LOGARITHM OF TOTAL VOC CONCENTRATION
IN THE PROCESSED SOIL - HIGH TEMPERATURE RUNS

Both moisture content of the feed soil and flow rate of inerts have negative regression coefficients. Therefore, increasing either of these variables would result in lowering the processed soil temperature. For these high temperature runs, moisture content of the processed soil also has a negative regression coefficient. It is suspected that this is due to the fact that all of these runs had processed soil temperatures well above the boiling point of water (i.e., 140 to 175°C). Within this regime, it is logical that an inverse relationship between processed soil temperature and moisture content would exist (i.e., the higher the processed soil temperature, the lower the soil moisture content).

10.1.2.3.2.2 Testing the validity of the equation. The validity of the correlation that was developed to estimate the temperature of the processed soil was tested using actual data. The actual soil temperatures corresponding to each test run as well as the estimated values are shown in Table 10-4. The correlation estimated the actual temperature within a deviation range of 0.25 percent to 0.85 percent. A graphical display of the actual and estimated values of the soil discharge temperatures is shown in Figure 10-4.
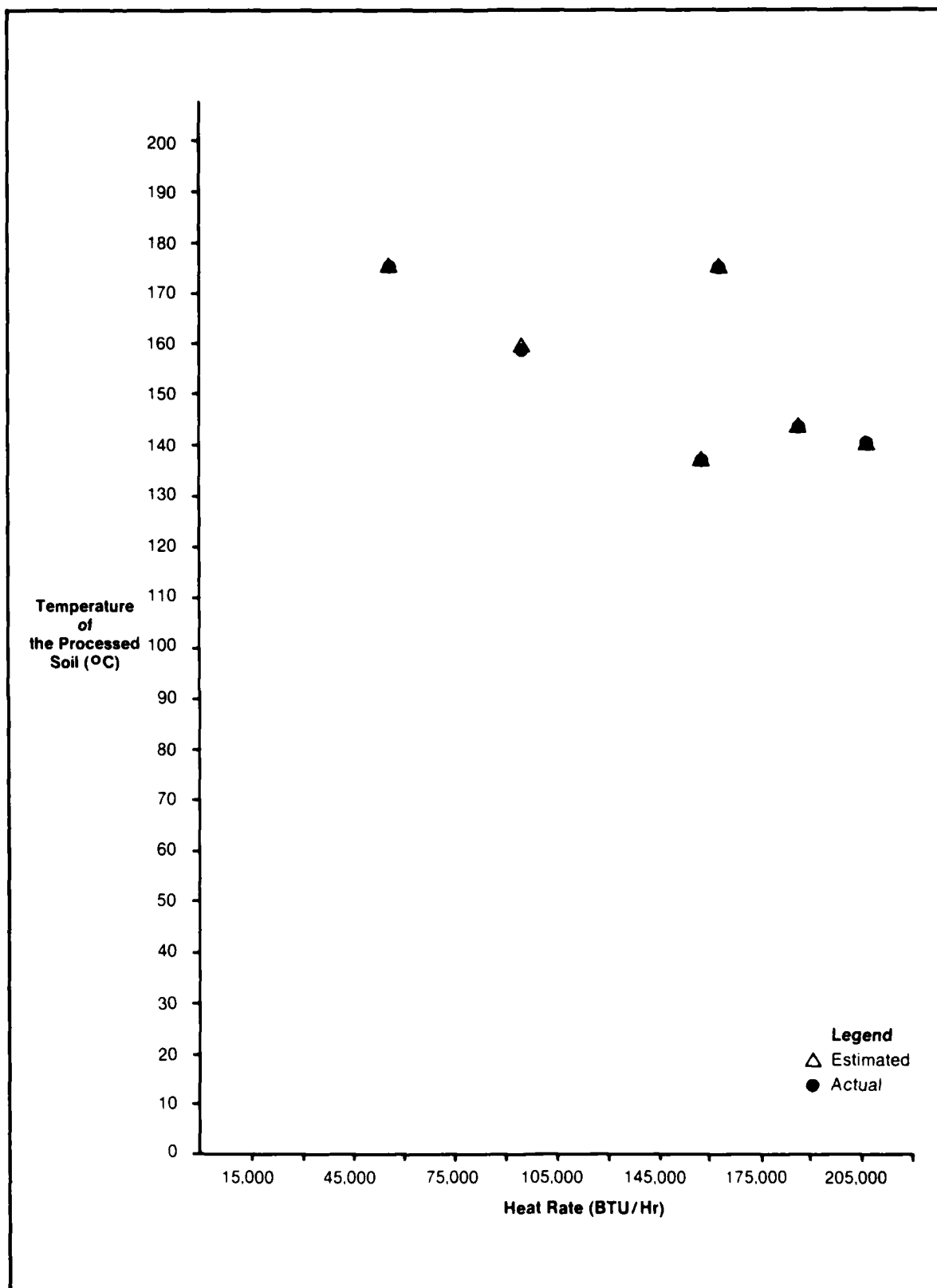
10.2 Emission control efficiency.

10.2.1 Controlled emissions.

10.2.1.1 Off-gas manifold system. Two modes of analysis were used to analyze the discharge gas in the three legs of the manifold systems: 1) a CEM system, and 2) a Bruker MM1 Mobile Mass Spectrometer. Each mode will be discussed separately in the following subsections.

10.2.1.1.1 CEM system. A comparison of the total VOC concentration as measured by the CEM system and GC/MS analyses is displayed in Appendix H, Table H-3 for the Phase I test runs and those Phase II test runs that were monitored. An AID was used during test runs 1 through 11; an OVA was used during test runs 12 through 18. Analysis of Table H-3 indicates that the OVA more accurately estimated the gross VOC concentrations in manifolds 1, 2, and 3 compared to the AID. The concentrations detected by the OVA during the Phase I test runs deviated 29 percent (average) from the GC/MS analytical values. Analysis of Table H-3, however, indicates that the OVA deviated from the

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TABLE 10-4.   COMPARISON OF ACTUAL AND ESTIMATED VALUES OF
             TEMPERATURE OF THE PROCESSED SOIL - HIGH
             TEMPERATURES

Test run	ln [TOT VOC's]$_{PS}$ (actual - °C)	ln [TOT VOC's]$_{PS}$ (estimated - °C)	Deviation between actual and estimated (percent)
10	158.66	159.26	0.38
11	137.34	137.84	0.36
12	143.27	143.78	0.35
13	175.27	174.44	0.48
14	175.33	175.77	0.25
15	140.30	139.12	0.85

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FIGURE 10-4   COMPARISON OF ACTUAL VERSUS ESTIMATED
VALUES OF TEMPERATURE OF THE PROCESSED
SOIL - HIGH TEMPERATURE RUNS

GC/MS analytical results by 89.41 percent during the Phase II test runs. This may be explained by considering the negative pressure which had to be overcome by the suction pump on the instrument. During Phase I test runs, the OVA was used in each of the three manifold lines each of which accounted for approximately one-third of the total flow. The suction pump on the OVA was obviously powerful enough to overcome the negative pressure in the lines. During the Phase II test runs, however, the OVA was connected to the afterburner inlet. The flow was three times higher at this location, and the negative pressure was greater; possibly, it was too high for the suction pump on the OVA to overcome. This may explain why the accuracy of the OVA for estimating VOC's in the discharge air was so much lower during the Phase II test runs. If the OVA is to be utilized in this capacity, the instrument manufacturer should be consulted to determine if the pump suction pressure is appropriate for the specific application.

10.2.1.1.2 Bruker MM1 Mobile Mass Spectrometer. The results from the Mobile Mass Spectrometer are displayed in Tables H-4, H-5, and H-6 in Appendix H. As mentioned, the MM1 was not calibrated for quantification, nor was the sampling method (simply placing the probe two inches from the sampling port) quantitative. The data can be used only in a relative sense, it cannot be converted to concentrations in air. Several features of the data are noted:

1. The base peak in all samples from Test Run 2 was at 166 atomic mass units (amu), which is characteristic of tetrachloroethene. However, since this compound was not a target compound during this run, relative quantification was not obtained. Analysis of Table 9-6 (VOC concentrations in the air discharge stream) indicates that during Test Run 2, the concentration of tetrachloroethylene was 237 ppm by volume. Tetrachloroethylene was the second major compound determined to be discharging from the unit. (Trichloroethylene was the most prominent at 375 ppm by volume.)

2. Generally, the samples from Test Run 4 contained the lowest levels of chlorinated hydrocarbons. Analysis of Table 9-6 lends credibility to this finding as shown by the following summary of the concentrations of total VOC's discharging in the air stream:
    Test Run 2 - 704 ppm by volume.
    Test Run 4 - 1.10 ppm by volume.
    Test Run 5 - 936 ppm by volume.

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3. 1,1,1-Trichloroethene registered the greatest response during Test Run 5; however, no detectable levels of this compound were determined to be present in the GC/MS analytical results.

4. Aliphatic hydrocarbons were detected to be present in Test Runs 2 and 4. A portion of this response probably arose from the presence of emissions from the oil heater. Note that levels of aliphatic hydrocarbons do not drop off during baseline sampling events.

5. The sample probe was placed inside pails of contaminated soil. Headspace sampling of feed soil also confirmed the presence of the chlorinated hydrocarbons seen during the soil processing.

6. Base line sampling was performed in the same location as port sampling except that the port valve was closed. Ambient air (e.g., clean outside air) gives readings of approximately 2-2.5 arbitrary log units.

In summary, comparison of the MM1 data with those obtained by conventional methods (charcoal sampling, GC/MS analysis) indicates that reliable qualitative information is generated by the MM1. As mentioned previously, the data can only be used in a relative sense; however, considerable attention needs to be given to the sampling methods and quantitative instrument calibration prior to any attempts to use this instrument for quantitative analysis.

10.2.1.2 Afterburner outlet. The gases discharged from the thermal processor were contained and directed to the afterburner for thermal destruction. Stack tests were conducted to determine if exhaust emissions were in compliance with Federal and state regulations. A detailed discussion of results is contained in Subsection 11.2.

10.2.2 Fugitive emissions. As discussed, the VOC concentrations in the excavated and feed soils were monitored to determine the gross amount of VOC's which escaped as fugitive emissions. Table 9-2 displays the VOC concentrations for the excavated and feed soils in Phase I and Phase II, respectively. A summary table showing the average concentration of the specific VOC's in the feed and excavated soils is shown in Table 10-5. Review of this table indicates that in every case except xylene which is only semivolatile, the concentration

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TABLE 10-5. COMPARISON OF VOC CONCENTRATIONS IN THE EXCAVATED AND FEED SOILS

Compound	VOC concentration in excavated soil (ppm by weight)	VOC concentration in feed soil (ppm by weight)	Fugitive emissions (percent by weight)
Dichloro-ethylene	252.30	135.40	46.33
Trichloro-ethylene	2,782.90	2,657.90	4.49
Tetrachloro-ethylene	744.60	599.20	19.53
Xylene	86.30	92.60	7.30
Other VOC's	38.40	20.20	47.40
Total VOC's	3,850.50	3,503.30	9.02

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in the feed soil is lower than that of the excavated soil. Based on the soil samples, this indicates that fugitive emissions of VOC's occurred from the time of excavation to the time the soils were fed to the unit. The amount of fugitive emissions ranged from 4.49 percent to 47.40 percent for the specific VOC's. The fugitive emissions corresponding to the average total VOC's were 9.02 percent. It is important to note that the fugitive emissions are based on the corresponding soil sample results and not air monitoring. As soil is extremely nonhomogeneous, these values represent estimated fugitive emissions only.

10.3   Results of optimization runs.

10.3.1   VOC removal along the length of the unit. As shown in Table 9-6, the VOC concentrations were monitored in each leg of the manifold system during Test Runs 19 through 23. Specific VOC's are discussed separately.

10.3.1.1   Dichloroethylene. Detectable levels of dichloro-ethylene were observed under the following test conditions:

1.   Residence Time - 60 minutes
     Soil Temperature - maximum (i.e., 224"C)
     Air Temperature - elevated
     Dichloroethylene Removal Efficiency - 92.71 percent
     Dichloroethylene in Processed Soil - 0.24 ppm by weight
2.   Residence Time - 90 minutes
     Soil Temperature - maximum (i.e., 218"C)
     Air Temperature - elevated
     Dichloroethylene Removal Efficiency - 100 percent
     Dichloroethylene in Processed Soil - below detection
     limits

As shown in Table 9-6, during the 60-minute test run, the dichororethylene removal rate increased from 0.50 ppm by volume in leg 1 to a maximum value of 0.60 ppm by volume in leg 2, then decreased to 0.50 ppm by volume in leg 3 of the manifold system. Since the dichloroethylene removal efficiency was only 92.71 percent, the contaminant was not completely removed from the soil. VOC's were still being removed, indicating that under the operating conditions, the residence time was insufficient for complete removal.

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In the case of the 90-minute test run, the dichloroethylene removal rate increased from 0.40 ppm by volume to 0.50 ppm by volume in legs 1 and 2, respectively, then decreased to a level that was below detection limits in leg 3. Analysis of the dichloroethylene removal efficiency (i.e., 100 percent) indicates that extension of the residence time, under similar operating conditions, removed a greater mass of dichloroethylene.

10.3.1.2   Trichloroethylene.   Detectable   levels   of trichloroethylene were present in those test runs operating under the following conditions:

1.   Residence Time - 60 minutes
      Soil Temperature - maximum (i.e., 224°C)
      Air Temperature - elevated
      Trichloroethylene Removal Efficiency - 67.48 percent
      Trichloroethylene in Processed Soil - 0.98 ppm by weight
2.   Residence Time - 90 minutes
      Soil Temperature - maximum (i.e. 218"C)
      Air Temperature - elevated
      Trichloroethylene Removal Efficiency - 99.54 percent
      Trichloroethylene in Processed Soil - 0.01 ppm by weight

As shown in Table 9-6, during the 60-minute test run the trichloroethylene removal rate was below detectable levels in leg 1 and increased to 0.30 ppm by volume in legs 2 and 3 of the manifold system. As evidenced by the trichloroethylene removal efficiency (i.e., 67.48 percent), the length of the unit was insufficient to remove the contaminant at the fixed operating conditions. Trichloroethylene was still being removed in the last portion of the unit.

During the 90-minute test run, the trichloroethylene removal rate increased from below detectable levels in leg 1, increased to 0.30 ppm by volume in leg 2, and decreased to below detectable limits in leg 3 of the manifold system. Analysis of the trichloroethylene removal efficiency (i.e., 99.54 percent), however, indicates that not all the contaminant was removed from the soil. This indicates that at the corresponding temperature and residence time, a residual amount of trichloroethylene will remain in the soil. In this case, the concentration of trichloroethylene in the processed soil was 0.1 ppm.

10.3.1.3   Tetrachloroethylene.   No detectable levels of tetrachloroethylene were determined to be present in the off-gas manifold system during Test Runs 19 through 23. Therefore, no analysis can be made regarding tetrachloroethylene removal rates.

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10.3.1.4 Xylene. Detectable levels of xylene were present in the off-gas manifold system during Test Runs 19 through 23, which operated under the following conditions:

1. Residence Time - 60 minutes
    Soil Temperature - 150°C
    Air Temperature - elevated
    Xylene Removal Efficiency - 99.89 percent
    Xylene in Processed Soil - 0.05 ppm by weight
2. Residence Time - 60 minutes
    Soil Temperature - maximum (i.e., 224°C)
    Air Temperature - elevated
    Xylene Removal Efficiency - 99.34 percent
    Xylene in Processed Soil - 0.08 ppm by weight
3. Residence Time - 75 minutes
    Soil Temperature - maximum (i.e., 233°C)
    Air Temperature - elevated
    Xylene Removal Efficiency - 99.76
    Xylene in Processed Soil - 0.04 ppm by weight
4. Residence Time - 90 minutes
    Soil Temperature - 150°C
    Air Temperature - elevated
    Xylene Removal Efficiency - 99.79
    Xylene in Processed Soil - 0.14 ppm by weight
5. Residence Time - 90 minutes
    Soil Temperature - maximum (i.e. 218°C)
    Air Temperature - elevated
    Xylene Removal Efficiency - 99.84
    Xylene in Processed Soil - 0.02 ppm by weight

As shown in Table 9-6, for the test run operating at 150°C and 60-minute residence time, the xylene removal rate increased from 2.50 ppm by volume in leg 1 to 8.10 ppm by volume in leg 2 and decreased to 2.40 ppm by volume in leg 3 of the unit. This removal trend indicates that although the volatization rate of xylene peaked in the central portion of the unit, contaminant was still being removed from the soil as it was discharged. This indicates that under the operating conditions, soil temperature and/or residence time were insufficient to completely remove the contaminant.

Review of the 60-minute test run that operated at the maximum soil discharge temperature indicates that the xylene removal rate increased to a maximum in leg 3 of the unit. This suggests that xylene was still being removed from the soil and that increasing processed soil temperature from 150°C to 224°C was not sufficient to effect the complete removal of xylene.

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A similar trend is displayed by the test run that operated at the maximum soil discharge temperature and 75-minute residence time. The xylene removal rate increased to a maximum in leg 3 of the manifold system, indicating that contaminant was still being removed from the soil as it was discharged from the unit. This suggests that increasing the residence time at maximum soil temperature was insufficient to completely remove the contaminant.

Analysis of the 90-minute test runs indicates that xylene was still being removed in the last portion of the unit. During the test run operating at a soil temperature of $150^\circ C$, the xylene removal rate decreased from 6.50 ppm by volume in leg 1 to 6.00 ppm by volume in leg 2 and, finally, to 2.60 ppm by volume in leg 3 of the manifold system. The test run that operated at the maximum soil discharge temperature (i.e., $218^\circ C$) displayed a xylene removal rate that increased from 1.10 ppm by volume in leg 1 to 1.80 ppm by volume in leg 2, then decreased to 1.30 ppm by volume in leg 3 of the manifold system. This indicates that the longest residence time and maximum soil discharge temperature attainable by the thermal processor were not sufficient to completely remove the xylene. In this case, the xylene residual was 0.02 ppm by weight in soil. Although a residual remained, in a remedial action, this level may be more than sufficient as a clean-up target. In fact, for all five runs, the xylene removal efficiencies were 99.34 percent or greater.

10.3.1.5 Other VOC's. Other VOC's (i.e. chloromethane, ethylbenzene, methylene chloride, 1,1,2,2-tetrachloroethane, and toluene) were detected during each test run. The operating conditions were as follows:

1.   Residence Time - 60 minutes
      Soil Temperature - $150^\circ C$
      Air Temperature - elevated
      Other VOC's Removal Efficiency - 97.11 percent
      Other VOC's in Processed Soil - 0.74 ppm by weight
2.   Residence Time - 60 minutes
      Soil Temperature - maximum (i.e., $224^\circ C$)
      Air Temperature - elevated
      Other VOC's Removal Efficiency - 84.11 percent
      Other VOC's in Processed Soil - 1.35 ppm by weight
3.   Residence Time - 75 minutes
      Soil Temperature - maximum (i.e., $233^\circ C$)
      Air Temperature - elevated
      Other VOC's Removal Efficiency - 98.88
      Other VOC's in Processed Soil - 0.28 ppm by weight

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4. Residence Time - 90 minutes
    Soil Temperature - 150°C
    Air Temperature - elevated
    Other VOC's Removal Efficiency - 96.29
    Other VOC's in Processed Soil - 1.43 ppm by weight

5. Residence Time - 90 minutes
    Soil Temperature - maximum (i.e. 218°C)
    Air Temperature - elevated
    Other VOC's Removal Efficiency - 97.50
    Other VOC's in Processed Soil - 0.53 ppm by weight

Contaminant was still being removed in leg 3 of the manifold system during each of the above test runs. This indicates that the operating temperatures and residence times were insufficient to completely remove the other VOC's. During the 60-minute test run at 150°C the contaminant removal rate increased from 1.10 ppm by volume in leg 1 to a maximum value of 5.30 ppm by volume in leg 2, and finally decreased to 1.20 ppm by volume in leg 3 of the manifold system. Analysis of the 90-minute test run that also operated at 150°C displays a similar trend. The other VOC's removal rate slightly decreased from 6.50 ppm by volume in leg 1 to 6.00 ppm by volume in leg 2 and further decreased to 2.60 ppm by volume in leg 3 of the manifold system. Comparison of these two test runs (i.e., 60 minutes at 150°C and 90 minutes at 150°C) indicates that the effect of extending the residence time beyond 60 minutes is minimal.

The remainder of the test runs operated at a maximum soil discharge temperature. The contaminant removal rate followed the same trend for the 60-minute and 75-minute test runs. The other VOC's removal rate increased over the length of the unit to a maximum value in leg 3 of the manifold system. During the 90-minute test run, the other VOC's removal rate increased from 1.10 ppm by volume in leg 1 to a maximum value of 1.80 ppm by volume in leg 2, and decreased to 1.30 ppm by volume in leg 3.

10.3.1.6   Total VOC's. At the target soil discharge temperature of 150°C, the general trend of the total VOC's removal rate is to peak in the first two-thirds of the unit, and drop off in the last portion of the processor. Total VOC's were still being removed from the soil as it was discharged from the unit. This indicates that the soil temperature and residence times were insufficient to completely remove the VOC's.

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At the maximum attainable soil discharge temperature, the general trend of the total VOC's removal rate is to increase along the length of the unit and reach a maximum value in leg 3 of the manifold system. This indicates that at the maximum attainable soil temperature and residence times evaluated, a residual of total VOC's will remain in the soil. However, the additional mass of VOC's removed by increasing soil temperature and residence time was relatively minute.

It is important to remember that the purpose of Test Runs 19 through 23 was to determine if general trends of contaminant removal exist. Simply because contaminant is still being removed in the last portion of the unit does not mean that in order to be effective a residence time of greater than 90 minutes and a soil discharge temperature of over $233^{\circ}C$ are required. The residual concentration is generally the single most important consideration in a remedial action. Although VOC's were still being removed in each test run that was analyzed, the residual VOC concentration in the processed soil may have been much lower than required in a clean-up effort.

10.3.2 Reproducibility of treatment. To the fullest extent possible, identical operating conditions were maintained during Test Runs 24, 25, and 26 to compare VOC removal efficiencies and thus determine the "reproducibility" of treatment. The operating conditions were as follows:

1. Residence Time - 60 minutes
2. Soil Discharge Temperature - $50^{\circ}C$
3. Air Inlet Temperature - ambient

The composition/conditions corresponding to the feed and processed soils are contained in Tables 9-3, 9-4, and 9-5. For convenience, a summary is included in Table 10-6. As shown on this table, the total VOC concentrations in the feed soil were not in the same order of magnitude. As discussed in Subsection 10.1.2.1.1, the concentration of total VOC's in the feed soil directly impacts the concentration of total VOC's in the processed soil for the low temperature runs. Since the operating conditions corresponding to all three test runs were "identical," the total VOC's concentration in Test Run 26 would be expected to be greater than that of Test Run 25, which in turn would be expected to be greater than that corresponding to Test Run 24. Analysis of Table 10-6 shows this to be the case. This lends credibility to the equations developed for estimating the total VOC concentration in processed soil for low temperature runs. If the equations hold, therefore, the treatment is reproducible if the feed soil conditions (i.e., moisture and total VOC concentration) are comparable. This is true for low, medium, and high operating temperatures.

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TABLE 10-6.   SOIL COMPOSITION/CONDITIONS FROM
             TEST RUNS 24, 25, AND 26
             (REPRODUCIBILITY OF TREATMENT)

	Test run 24	Test run 25	Test run 26
Total VOC concentration in feed soil (ppm by weight)	365.52	1,650.60	3,324.00
Total VOC concentration in processed soil (actual) (ppm by weight)	7.42	43.94	111.99
Total VOC concentration in processed soil (estimated by correlation for low temperature test runs) (ppm by weight)	6.72	56.05	97.41
VOC removal efficiency	98.22	97.55	97.02

10.3.3 Reprocessing of treated soils that contain a contaminant residue. Test Runs 27 and 28 evaluated the feasibility of reprocessing soils that still contained a residual concentration.

Operating conditions for Test Runs 27 and 28, respectively, were as follows:

1. Residence Time - 60 minutes
2. Soil Discharge Temperature - maximum (i.e., 174.58°C)
3. Air Inlet Temperature - ambient

1. Residence Time - 90 minutes
2. Soil Discharge Temperature - maximum (i.e., 185°C)
3. Air Inlet Temperature - ambient

Processed soils from Test Run 2 were selected for treatment, primarily because the moisture content was relatively high (i.e., 7 percent) and dust generation would be minimized during feed operations. For convenience, a summary of soil composition/conditions corresponding to Test Runs 27 and 28 is included in Table 10-7. As shown in this table, the total VOC concentrations in the feed soil vary by nearly a factor of four; however, as discussed in Subsection 10.1.2.3.1, the total VOC concentration in the feed soil does not have a strong impact on the concentration in the processed soil for high temperature runs. A comparison can therefore be made. Analysis of Table 10-7 indicates two things. First, a residual concentration existed in the processed soils of each run. Second, increasing the residence time reduced the residual concentration significantly (even though the feed concentration in the 90-minute test run was higher than that of the 60-minute test run). As a reminder, the purpose of a remedial action will be to process soil to achieve a target VOC concentration. Although a residual existed in the processed soils corresponding to Test Runs 27 and 28, the VOC concentrations (i.e., 2.76 ppm and 0.92 ppm, respectively) may be more than sufficient when compared to the target concentration.

10.4 Miscellaneous observations.

10.4.1 Soil density. In general, the density of the feed soil was higher than that of the processed soil. The actual values are contained in Appendix F. For convenience, a summary of the average soil densities corresponding to the high, medium, and low temperature test runs is shown on Table 10-8. As shown, the difference in operating temperatures did not significantly affect the processed soil densities.

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TABLE 10-7. SOIL COMPOSITION/CONDITIONS FROM
TEST RUNS 27 AND 28
(REPROCESSING OF TREATED SOILS)

	Test run 27	Test run 28
Total VOC concentration in feed soil (ppm by weight)	226.00	831.90
Total VOC concentration in processed soil (ppm by weight)	2.76	0.92
VOC removal efficiency	98.92	99.91

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TABLE 10-8. AVERAGE SOIL DENSITIES FOR LOW,
MEDIUM, AND HIGH TEMPERATURE TEST RUNS

Density (#/cu ft)	Low temperature test runs	Middle temperature test runs	High temperature test runs
Feed Soil	91.23	85.47	94.02
Processed Soil	75.29	72.62	75.96

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10.4.2 Soil appearance. The feed soils were generally wet, nonhomogeneous, clumps of soil. Native soil was a light orange-brown in color. Contaminated (fill) soils were very dark and sometimes appeared to be saturated with a black oily substance.

The processed soils were dry, homogeneous, fine particles. Due to the decrease in moisture content, the processed soils had a tendency to generate fugitive dust. Processed soils that corresponded to the black contaminated (fill) soils retained their dark appearance.

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11.   COMPARISON OF TEST RESULTS TO REGULATORY CRITERIA

The following subsections deal with portions of the Code of Federal Regulations (CFR). The referenced sections are included in Appendix H.

11.1   Processed soils.

11.1.1   Criteria for classification of a hazardous waste. According to 40 CFR Part 261, a solid waste is classified as a hazardous waste if it meets at least one of the following criteria:

1.   It is not excluded from regulation as a hazardous waste under 261.4 (b) (i.e., household waste, solid waste returned to the soil as fertilizer, mining overburden, fly-ash waste, drilling fluids, wastes which fail the EP toxicity test because chromium is present, solid waste from the extraction, benefici- ation, and processing of ores and minerals, cement kiln dust waste, solid waste which consists of wood or wood products which fails the EP toxicity test only).

2.   It exhibits any of the characteristics of hazardous waste identified in Subpart C of 40 CFR Part 261 (i.e., ignitability, corrosivity, reactivity, EP toxicity).

3.   It is listed in Subpart D of 40 CFR Part 261 and has not been excluded from the lists in Subpart D under 40 CFR 260.22 (i.e., regulatory amendment to exclude a waste at a particular facility because the waste does not meet any of the criteria under which the waste was listed as a hazardous waste).

4.   It meets the criteria listed in 40 CFR 261.11 (i.e., exhibits any of the characteristics of hazardous waste identified in Subpart C; it has been found to be fatal to humans in low doses; it contains any of the toxic constituents listed in Appendix VIII).

5.   It is a mixture of a solid waste and a hazardous waste that is listed in 40 CFR Subpart D solely because it exhibits one or more of the characteristics of hazardous waste identified in 40 CFR Subpart C, unless the resultant mixture no longer exhibits any characteristic of hazardous waste identified in Subpart C.

6.   It is a mixture of solid waste and one or more hazardous wastes listed in 40 CFR Subpart D and has not been excluded under 40 CFR 260.22.

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11.1.2 Classification of LEAD processed soils. The classification of processed soils must be on a case-by-case basis depending on the constituents in the feed soils. In this case, the LEAD processed soils are classified as a hazardous waste if any of the following criteria are met:

1. The soil constituents exhibit any of the characteristics of hazardous waste identified in Subpart C of 40 CFR Part 261. The potential characteristics would be ignitability (i.e., xylene) and toxicity (i.e., trichloroethylene and tetrachloroethylene).
2. The concentrations of those contaminants listed in Subpart D of 40 CFR Part 261, i.e., trichloroethylene (F002), tetrachloroethylene (F002), and xylene (F003) or Appendix VIII (i.e., trans-1,2-dichloroethylene) are detectable.

11.1.3 Delisting of the processed soils. It is possible to have the processed soils that are technically classified as hazardous waste "delisted" from Federal regulations. According to 40 CFR 260.20, the Administrator of the EPA may be petitioned to modify or revoke any provision in the CFR. Specifically, 40 CFR 260.22 includes regulations concerning petitions to amend Part 261 to exclude a waste produced at a particular facility. To be successful, the petitioner must demonstrate to the satisfaction of the Administrator that the waste does not meet any of the criteria under which the waste was listed as a hazardous waste.

In the case of LEAD soils, the petitioner must demonstrate all of the following:

1. The processed soils do not contain those compounds listed in Subpart D of 40 CFR Part 260 in sufficient concentration to exhibit the characteristics of ignitability (due to xylene) or toxicity (due to trichloroethylene and tetrachloroethylene).
2. The processed soils do not contain those toxic constituents listed in Appendix VIII (i.e., trans-1,2-dichloroethylene) in sufficient concentration to pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported or disposed of, or otherwise managed.
3. The processed soils do not exhibit the characteristics of ignitability, corrosivity, reactivity, or EP toxicity.

11.2 Stack emissions. Stack tests were conducted during Test Runs 8, 9, and 10. Stack emissions were tested for VOC's, particulates, hydrogen chloride, and fixed gases.

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11.2.1 Principal organic hazardous constituent (POHC) destruction and removal efficiency. Specific regulations for nonincinerator thermal treatment processes have not been promulgated. Therefore, this section compares the results of this program to the Federal regulations for hazardous waste incineration contained in 40 CFR 264.340 to 264.351.

According to 40 CFR 264.342, the POHC's in the waste feed must be treated to the extent required by the performance standard of 264.343. For the destruction of gases generated by the LEAD soils, the POHC's were identified to be trichloroethylene, dichloroethylene, tetrachloroethylene, and xylene. The performance standard dictates that an incinerator must achieve a destruction and removal efficiency (DRE) of 99.99 percent for each POHC. DRE is determined for each POHC from the following equation:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}}$$

Where: W_{in} = mass feed rate of one POHC in the waste stream feeding the incinerator

W_{out} = mass emission rate of the same POHC present in exhaust emissions prior to release to the atmosphere

Stack tests conducted during Test Runs 8, 9, and 10 indicated that no detectable levels of the POHC's were determined to be present in the exhaust emissions. The DRE for each POHC, therefore, was 100 percent during each of the three selected test runs.

11.2.2 Particulate emissions. According to 40 CFR 264.343 (c), an incinerator burning hazardous waste must not emit particulate matter in excess of 180 milligrams per dry standard cubic meter (0.08 grains per dry standard cubic foot) when corrected for the amount of oxygen in the stack gas according to the formula:

$$P_i = P_m \times \frac{14}{21-y}$$

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Where: P_c = the corrected concentration of particulate
matter

P_m = the measured concentration of particulate
matter

Y = the measured concentration of oxygen in the
stack gas

The particulate emissions corresponding to Test Runs 8, 9, and 10 were 0.071 grains/dry standard cubic foot, 0.04 grains/ dry standard cubic foot, and 0.06 grains/dry standard cubic foot, respectively. Stack tests demonstrated that particulate emissions during the three selected test runs were below the regulatory limit of 0.08 grains/dry standard cubic foot.

11.2.3   HCl emissions. According to 40 CFR 264.343(b), an incinerator burning hazardous waste and producing stack emissions of more than 1.8 kilograms per hour (4 pounds per hour) of HCl must control HCl emissions such that the rate of emission is not greater than the larger of either 1.8 kilograms per hour or 1 percent of the HCl in the stack gas prior to entering any pollution control equipment. Since there was no equipment to control the amount of hydrogen chloride in the afterburner off-gases, precautions were taken to ensure that HCl emissions did not exceed the allowable rate of 4 pounds per hour. In the planning stages of the project, the feed soil rate was determined based on an assumed concentration (i.e., 10,000 ppm) of dichloroethylene (the major contaminant), complete conversion to HCl, and the maximum allowable emission rate of 4 pounds of HCl per hour. The corresponding feed soil rate was approximately 500 pounds per hour. The HCl mass emission rates corresponding to Test Runs 8, 9, and 10 were 0.75 lbs/hr, 1.80 lbs/hr, and 1.55 lbs/hr, respectively. Therefore, the HCl mass emission rates did not exceed the regulatory limit of 4 lbs/hr. A discussion of potential equipment to control HCl emissions is contained in Section 12.

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12. FULL-SCALE DESIGN CONSIDERATIONS

12.1 <u>Modifications to full-scale design</u>. The purpose of the pilot investigation was to test the feasibility of the thermal stripping technology. As such, the equipment was pilot scale and could only handle a relatively low soil feed rate (i.e., 385 pounds per hour maximum). A full-scale system would be designed to handle much larger soil feed rates.

12.1.1 Feed system. A practical application would enable backhoes to directly dump the contents of their bucket into a large feed hopper. A screw conveyor, or similar piece of equipment, would be located in the bottom of the hopper to feed soil to the unit at the appropriate rate. As the soil may contain rocks and other large items, it would be advisable to equip the feed soils hopper with a mesh screen that would segregate larger items.

12.1.2 Thermal processor. The size of the thermal processor would be large enough to accommodate a high soil feed rate. The tolerance between the flights of the screws and the trough would be wide enough to process rocks or large items without jamming the system. In the event of a jam, the rotation of the screws would be able to reverse direction to clear the jam. It would also be beneficial to equip the dome of the processor with ports for easy access in the event of a jam. As a precaution, the screws and feed system should be electrically connected to the soil discharge system. If there were a jam or clog at the soil discharge conveyor, the screws and feed system would stop operation. This would prevent soil from backing up in the processor. An alarm system should sound when a component becomes nonoperational. A full-scale system should also be designed to operate with circuit breakers, not fuses.

12.1.3 Heating medium. Although Therminol 66 was used in this application, it may be more economical to employ steam as a heating medium, depending on availability of an uncontaminated water source and the desired soil discharge temperature.

12.1.4 Soil discharge. A screw conveyor would also be used to discharge soils. The screws would have the option to operate in a reverse direction to clear jams. Since dust generation is likely, perhaps a fine mist of water could contact the soils upon discharge. The unit could be elevated to allow direct discharge into a dump truck or storage bin.

12.1.5 Air systems. It is important to inhibit air infiltration to the processor in order to control the amount of combustion air, temperature, etc. Therefore, provisions must be made to ensure the system is airtight. Sufficient head can be maintained in the feed hopper by ensuring sufficient soil is available to seal the unit. However, a rotary-valve would be required in the discharge end of the processor. To preclude jamming problems inherent in the pilot study, the vanes of the valve should be constructed of flexible material such as rubber. The valves should be able to operate in both directions (i.e., clockwise, counterclockwise) so that in the event of a jam, the direction of the valve could be reversed in order to clear the jammed material.

12.1.5.1 Inlet air. As demonstrated, an elevated air inlet temperature does not enhance contaminant volatilization; therefore, ambient air would be utilized in a full-scale operation.

12.1.5.2 Discharge air. During the pilot investigation, multiple air discharge lines were used to evaluate the contaminant removal trends. However, there would be no need to have more than one discharge air line in a full-scale system. Using the discharge air as combustion air worked well in this application; however, in a long-term situation it would not be advisable. Particulate/dust would most likely clog the burner ports and induced draft fan.

A full-scale system would most likely require pollution control equipment. Anticipated emission problems include particulate and HCl/acidic gases. To address these concerns, a number of options are available, depending on the level of control required.

If particulate emissions are the only problem (i.e., the concentration of chlorinated VOC's in the feed soil are relatively low and the corresponding mass of HCl generated is below the allowable limit of 4 pounds per hour), a simple process modification may be sufficient. For example, the dry processed soil could be moistened with a water mist at the discharge end of the unit, reducing dust generation and particulate in the off-gases. If the water spray was not sufficient, a mechanical separator (i.e., cyclone) could be installed between the processor and afterburner where the temperature and flow of the air stream are low. For even greater particulate removal, a fabric filter could be used instead of a mechanical separator. However, since a high moisture content is inherent in the discharge air stream, it may be necessary to elevate the temperature of the stream to assure that the water remains in the vapor form.

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If HCl/acidic gases are the only problem, a scrubber system could be installed downstream of the afterburner. Discharge gases (approximately 1000°C) would be cooled in a quench section prior to entering a packed tower where the acidic off-gas stream would be scrubbed with a caustic solution for neutralization. The scrubber liquor (i.e., water and salts generated upon combination of acid and caustic) would technically be classified as a hazardous waste. However, a petition could be submitted to the appropriate regulatory agency to request that the scrubber liquor be "delisted." If successful, the delisted liquor could be discharged to a publicly owned treatment works (POTW).

In the event that particulate and HCl/acidic gases are both problems, a combination system including a venturi scrubber (to quench the discharge gases and to remove particulate) followed by a packed tower (to scrub acidic gases) could be installed downstream of the afterburner.

12.2 Example calculation using correlations to design a full-scale system. The correlations presented in Section 10 can be used for design of a full-scale system to treat LEAD site soils. The following example is presented for illustration:

Hypothetical site characteristics:

TOT VOC's$_{FS}$ = 1,000 ppm
M_{FS} = 20 percent by weight
TOT VOC's$_{PS}$ = 10 ppm (i.e., assumed clean-up objective)

Suppose, in order to expedite cleanup, the feed rate of soil to the unit is high, e.g., two tons per hour (4,000 pounds per hour). Assume a hot oil source is available to supply 100,000 Btu per hour. The variables must be in the correct units to utilize the equation.

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$$\text{TOT VOC's}_{FS} \ (\#/hr) = \frac{1000 \ \# \ \text{TOT VOCFS}}{10^6 \ \# \ \text{soil}} \ x \ \frac{4000 \ \# \ \text{soil}}{hr}$$

$$= 4.0 \ \#/hr$$

$$\text{TOT VOC's}_{PS} \ (\#/hr) = \frac{10 \ \# \ \text{TOT VOCPS}}{10^6 \ \# \ \text{soil}} \ x \ \frac{4000 \ \# \ \text{soil*}}{hr}$$

$$= 0.04 \ \#/hr$$

Review of the range of values associated with each correlation for total VOC's in the feed soil indicates that the equation developed for high temperatures may be used (i.e., the range of total VOC's in the feed soil was 0.135 #/hr to 4.651 #/hr).

Substituting the appropriate values will enable derivation of the residence time required for processing.

$$\ln [\text{TOT VOC's}_{PS}] = 1.5843 - (3.212 \ x \ 10^{-5} \ x \ H) + (0.2784 \ x \ M_{FS}) - (0.1993 \ x \ T_R)$$

$$\ln [0.04] = 1.5843 - (3.212 \ x \ 10^{-5} \ x \ 100,000) + (0.2784 \ x \ 20) - (0.1993 \ x \ T_R)$$
$$- 3.219 = 1.5843 - 3.212 + 5.568 - (0.1993 \ x \ T_R)$$

Solving for residence time:

$$T_R = \frac{-3.219 - 1.5843 + 3.212 - 5.568}{-0.1993}$$

$$T_R = 35.92 \ \text{minutes (assuming a processed soil temperature of 150°C)}$$

If the residence time is fixed, the same procedure may be repeated, solving for the value of the heat rate.

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*This is a conservative estimate since the evaporation of moisture is not taken into account.

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12.3 **Economics of a full-scale system**. Evaluation of the economics of a full-scale system was not undertaken as part of this study. Rather, as part of a separate subtask, a study will be completed to evaluate the economics corresponding to various sites (i.e., different size and waste characteristics). The evaluation will include the general approach outlined below:

(a) Four separate sizes of low temperature thermal treatment systems will be evaluated in order to determine the sensitivity of project costs to alternative system sizes.

(b) Two separate system configurations will be evaluated (i.e., Option 1 - Without Flue Gas Scrubbing and Option 2 - With Flue Gas Scrubbing) in order to determine the sensitivity of project costs to the requirement for flue gas scrubbing.

(c) Three separate quantities of soil to be processed will be evaluated in order to determine the sensitivity of project costs to site size (i.e., soil quantity) and to determine which system sizes are most cost effective for various size sites.

(d) A uniform set of economic assumptions will be established for all options evaluated so that the costs can be compared on an "apples-to-apples" basis. A sensitivity analysis will be presented to determine the impact upon project costs of varying the economic assumptions.

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13. CONCLUSIONS AND RECOMMENDATIONS

13.1 <u>Conclusions</u>. Based on review of the data associated with all test runs, the following conclusions are presented:

1. The low temperature thermal stripping technology is an effective means of removing VOC's from soil.

2. VOC removal efficiencies associated with an elevated air inlet temperature are generally lower than those associated with an ambient air inlet temperature.

3. An exponential relationship exists between VOC concentrations in the processed soil and those input and control variables determined to have a significant contribution in the statistical analysis.

4. Correlations developed to predict the VOC concentrations in the processed soil and soil discharge temperature are site-specific and applicable to three distinct soil discharge temperature ranges. The validity of the correlations for different soil and contaminant types is questionable.

5. Moisture in the feed soil and residence time are statistically significant variables in all correlations (i.e., low, medium, and high soil discharge temperatures).

6. An OVA can be utilized to estimate the VOC concentrations in the discharge air stream; however, the instrument manufacturer should be consulted to determine if the pump suction pressure is appropriate for the specific application.

7. A mobile mass spectrometer can be utilized to generate reliable qualitative information concerning VOC's in the discharge air stream. However, considerable attention needs to be given to sampling methods and quantitative instrument calibration.

8. Fugitive emissions of VOC's occurred from the time of excavation of soils to the time soils were fed to the thermal processor (estimated total VOC's fugitive emissions was 9.02 percent).

9. The low temperature thermal processor can be designed to achieve specific VOC clean-up objectives. The level of residual VOC's in the processed soil is a direct and predictable function of:

    (a) VOC concentration in the feed soil.
    (b) Processed soil temperature.
    (c) Soil residence time within the thermal processor.
    (d) Heat input rate to the thermal processor.
    (e) Moisture content of the feed soil and processed soil.

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Depending on the VOC type and range of concentrations in the feed soil for a specific site, the other variables (i.e., processed soil temperatures, residence time, heat input, and moisture content) can be incorporated within the overall system design to achieve a wide range of target clean-up levels (i.e., 100 ppm, 10 ppm, 1 ppm, etc.). However, if the clean-up objective is "no detectable VOC's in the processed soils," then, based on this field demonstration program, a processed soil temperature of higher than 233°C and a residence time of over 90 minutes would be required.

10. Treatment is reproducible and comparable if feed soil composition/conditions are similar (i.e., moisture, VOC concentration).

11. Reprocessing of treated soils that still contained a contaminant residue reduced the VOC concentration significantly; however, a residual still existed.

12. Stack tests conducted during Test Runs 8, 9, and 10 indicated that no detectable levels of the principal organic hazardous constituents (POHC's) were determined to be present in the exhaust emissions (i.e., 100 percent destruction removal efficiency (DRE)).

13. Stack tests conducted during Test Runs 8, 9, and 10 demonstrated that particulate and hydrogen chloride emissions did not exceed regulatory limits during these test runs (No comment can be made regarding other test runs as no stack testing was completed).

13.2 Recommendations. Based on the results of this field demonstration program, the following recommendations are presented:

1. Further development of the low temperature thermal stripping technology is warranted. This further development should include:

   - An in-depth economic analysis of alternative system sizes and configurations and selection of the most advantageous alternative.
   - Preparation of performance specifications and a technical data package for the selected alternative(s).
   - Development of heat transfer coefficients for the thermal processor.

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2. The economic analysis should include a comparison to another baseline technology such as rotary kiln incineration.
3. The technical data package should be designed to provide sufficient information to support bid document preparation for application of this technology at DOD installations.
4. Additional pilot scale testing is recommended prior to the design of a full-scale system for soil and contaminant types other than those tested.

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